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ESTUARINE POLLUTION IN THE STATE OF HAWAII. VOLUME I: STATEWIDE STUDY

Doak C. Cox, et al

Hawaii University
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March 1970

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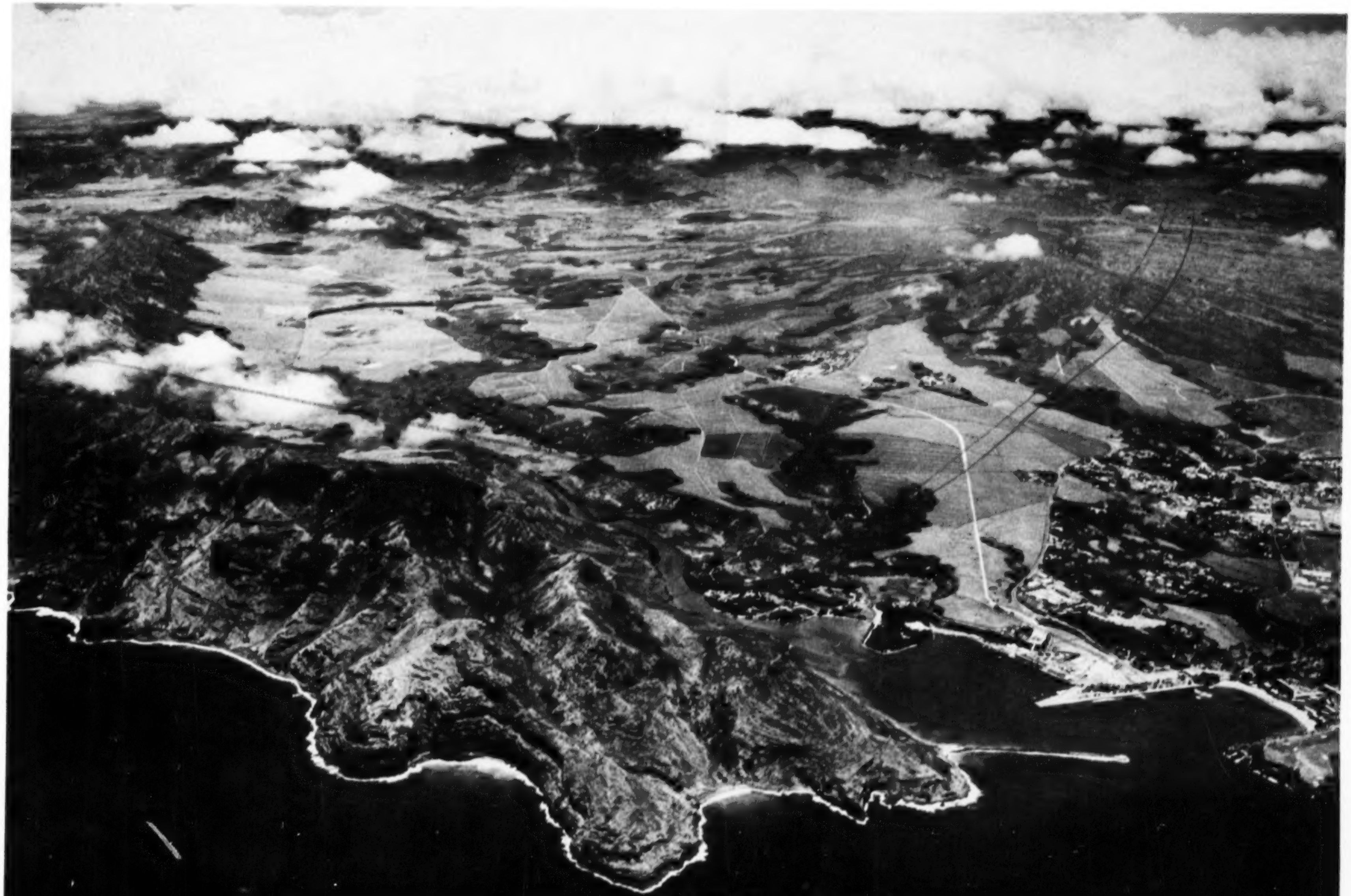

FRONTISPIECE. NAWILIWILI BAY, KAUAI. FROM THE LEFT THE HULEIA RIVER, ENTERS THE HEAD OF THE BAY WHICH, PROTECTED BY AN ARTIFICIAL PROMENTORY, IS BEING SILTED. NAWILIWILI HARBOR OCCUPIES THE MAIN PORTION OF THE BAY AND KALAPAKI BEACH IS ON THE RIGHT. THE FIELDS ON THE FAR LEFT, NEXT TO THE HAUPU RANGE, ARE PASTURES. THOSE IN THE CENTER, ON THE SLOPES OF KILOHANA CONE, WHOSE CRATER IS VISIBLE JUST ABOVE A SMALL CLOUD IN RIGHT CENTER, ARE SUGAR CANE. THE TOWN AND MILL OF LIHUE ARE ON THE RIGHT. IN THE BACKGROUND THE SLOPES OF THE WAIALEALE MASSIF RISE BENEATH THE CLOUD CAP. (PHOTO COURTESY OF AGATIN T. ABBOTT.)

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TECHNICAL REPORT NO. 31

ESTUARINE POLLUTION IN THE STATE OF HAWAII

VOL. I—STATEWIDE STUDY

MARCH 1970

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PREFACE

The This report is the result of a one-year study of pollution of estuaries in the State of Hawaii, undertaken by the University of Hawaii for the Federal Water Pollution Control Administration, ~~under contract no. 14-12-446.~~

Estuarine pollution is both a local and a national concern. Among faculty members of the University of Hawaii concerns with the ecological effects of pollution in estuaries in general, and Kaneohe Bay on Oahu in particular, had been mounting for some time. There were also concerns with the growing problems of waste disposal and with the physical, biological, and economic implications of recently adopted Water Quality Standards. At the national level, the Federal Water Pollution Control Administration was authorized and instructed under the Clean Water Restoration Act of 1966 to undertake a National Estuarine Pollution Study.

The study reported here grew out of initial correspondence begun in 1967, and particularly discussions held in December of that year, between interested faculty members and representatives of the FWPCA. Field work was initiated early in June 1968 with the interim support of the University's Office of Research Administration and expanded rapidly following the approval of the contract on 29 June 1968. A progress report was submitted to FWPCA in December 1968 (Water Resources Research Center Memorandum Report No. 15). Field work was terminated 30 June 1969, when a first draft of this report was transmitted to the FWPCA.

The study included two major projects, a statewide review of estuaries and their pollution based on already existing information, Vol. 1 of this report, and a special study of ecological factors and pollution in Kaneohe Bay, Vol. 2 of this report. end It involved faculty from several units of the University and administrative assistance of the Hawaii Institute of Marine Biology and the Agricultural Economics Department as well as that of the Water Resources Research Center.

Under the general coordination of a committee composed of V. E. Brock, N. C. Burbank, Jr., D. C. Cox (chairman), J. R. Davidson, and L. S. Lau, a number of subprojects were organized as follows:

Subproject	Manager	Supporting Unit	Administrative Unit
Statewide Study	R. J. Fuchs[1] D. C. Cox[2]	Geography Dept. WRRC	WRRC
Kaneohe Study			
Sedimentation	R. M. Moberly, Jr.[1] P. F. Fan[2]	Geoscience Dept. Haw. Inst. Geophys.	WRRC
Organics		Oceanography Dept.	HIMB
Plankton		Oceanography Dept.	HIMB
Mineralization		Microbiology Dept.	WRRC
Sanitary Quality		Public Health Sch.	WRRC
Alternatives	L. S. Lau	WRRC	WRRC
Economics	J. R. Davidson	Agr. Econ. Dept.	Agr. Econ.

[1] at beginning of study [2] at end of study

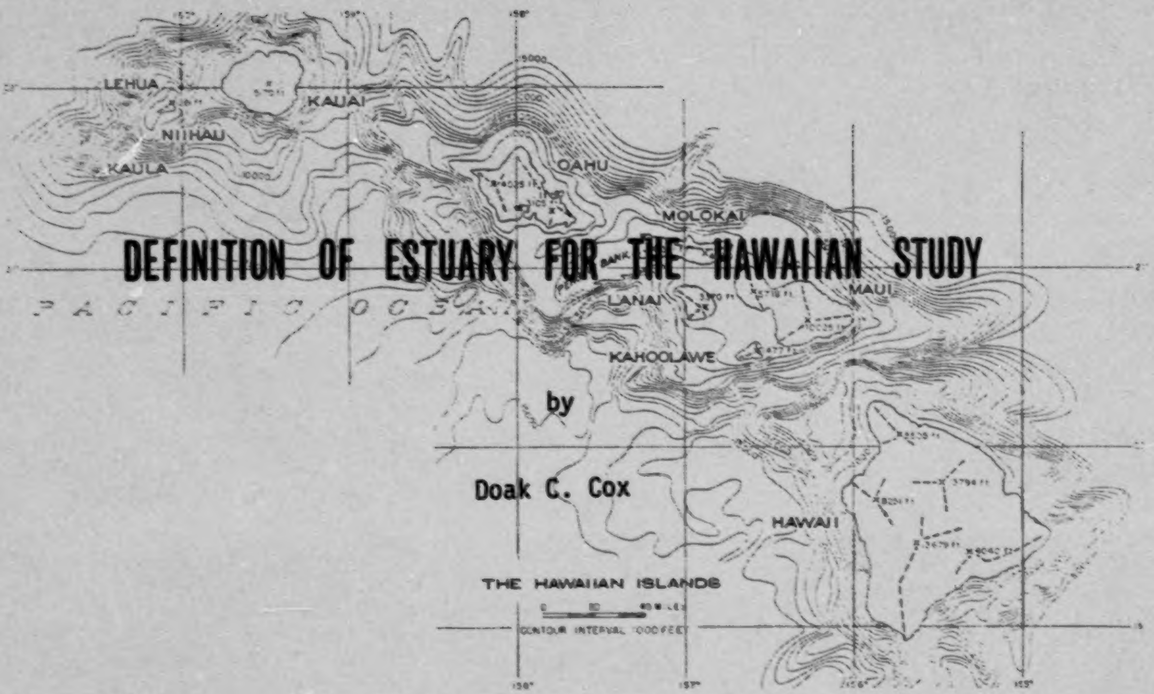
It is a pleasure to acknowledge the interest and assistance of concerned members of the staff of the FWPCA, especially Harold Berkson of the Washington Office, who served as project officer, James McCarty of the San Francisco Office, and Donald Mausshardt of the Honolulu Office. H. S. Odum of the University of North Carolina who was making a more general study of estuarine pollution under the National Study visited Hawaii during the course of the study and subsequently exchanged information with us. The help of a large number of others who were of assistance in various ways is acknowledged in the various parts of the report.

It should, perhaps, be emphasized here that no study with a duration of only a year, no matter how intensive could be expected to provide final and definitive answers to the major problems associated with pollution, its effects, and its control. The ecological and socio-economic processes involved are too complex. The study has, however, delineated areas needing additional research, and we hope it will serve as a useful interim tool in a much needed management program.

DEFINITION OF ESTUARY FOR THE HAWAIIAN STUDY

by

Doak C. Cox



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DEFINITION OF ESTUARY FOR THE HAWAIIAN STUDY

The term estuary has been defined and used in a variety of ways, some of the meanings assigned to it even being mutually exclusive. The etymology of the term and its definitions and usages are here reviewed to determine the definition most suitable for use in the University of Hawaii study of estuarine pollution in the state of Hawaii. Although the definition of an estuary and its distinction from other similar features is less important than the recognition and quantification of the important characteristics that might be used to make the distinction, it is still desirable that estuary, as a technical term, have a precise meaning as possible. Even Russell (1967) who regards taxonomic exercises as "fruitless and unjustified because our knowledge of coastal features is so incomplete" grants that "it is necessary to recognize major types." Special attention is given here to the various geomorphic, hydrodynamic, and hydrochemical criteria used in distinguishing estuaries. Typical sedimentological and biological assemblages have been described as estuarine, but these seem to be defined on the basis of their typical occurrence in estuaries identified on the basis of geomorphology, tidal behavior, and salinity rather than used as criteria for identifying estuaries.

Etymology and Common Usage

The etymology sometimes indicated for estuary, from the Latin *aestus* = heat, boiling, bubbling, tide, is indirect. The word comes to English direct from the Latin *aestuarium,* from *aestus* + *arium* (suff. = place of _______). *Aestuarium* in Roman times had two oceanographic meanings:

"1. Low ground covered by the sea at high water," and "2. A firth, creek, or part of the river up which a tide flows" (Simpson, 1960).

In French usage both meanings have persisted, the first, however, being restricted to broad embayments, *e.g.* (Larousse, 1930): "Sinuosité du littoral, qui n'est couverte l'eau quá marée haute. 2. Golfe formé par l'embouchure d'un fleuve." (1. A curve of the shore which is not covered by water except at high tide. 2. A gulf formed by the mouth of a river.)

In English usage the first meaning has become very rare. Johnson (1773) defined estuary as "an arm of the sea; the mouth of a lake or river in which the tide reciprocates; a firth." Modern English usage may be indicated by quotations from standard dictionaries and encyclopedias:

Oxford English Dictionary (1933): "1. *gen.* A tidal opening, an inlet or creek through which the tide enters; an arm of the sea indenting the land. Rare in modern use. 2. *spec.* The tidal mouth of a great river, where the tide meets the current of fresh water."

Webster's Third International Dictionary (1961): "1a: A water passage (as the mouth of a river) where the tide meets the current of a stream; tidal river. b: An arm of the sea at the lower end of a river. 2: A drowned river mouth caused by the sinking of the land near the coast."

New International Encyclopedia (1915): "The widened channel at the mouth of a river in which there is a marked tidal action. An estuary is usually formed by submergence or drowning of the river valley which is then subjected to the erosive action of tides and waves."

Encyclopedia Britannica (1962): "The mouth of a river where sea and fresh water meet and where tidal effects are conspicuous. An estuary may result from the long-continued joint action of river and tidal erosion confined to a narrow structural depression, or it may be the drowned lower portion of a river valley."

Encyclopedia Americana (1965): "When a shore line is sinking or has been recently depressed, rivers, unless large and heavily charged with sediments, have their valleys invaded by the encroaching sea, forming roughly funnel-shaped bays. Such bays are estuaries..."

Even excluding the first Larousse meaning of the intertidal zone of bays in general and the first Oxford and Johnsonian meaning of inlets not necessarily related to rivers, there is some disagreement among the several definitions. Tidal rivers, not involving submergence, would be excluded by the *Encyclopedia Americana*. Drowned valleys not subject to tidal action would be included only by Webster. Unfortunately the technical literature introduces even more inconsistencies.

Geomorphology

The earliest technical definition noted by the *Glossary of Geology and Related Sciences of the American Geological Institute* (Howell, 1939) is that of Lyell (1834): "Inlets of the land, which are entered by both rivers and the tides of the sea." This definition, like most of the common English ones, includes both a restriction to inlets of some sort and a relation to rivers, as well as the tidal action indicated by the etymology. Both the AGI Glossary and the oceanographic glossary of Hunt and Groves (1965) quote two Beach Erosion Board (1964) definitions: "1. That portion of a stream influenced by the tide of the body of water into which it flows; 2. a bay, as the mouth of a river, where the tide meets the river current."

The AGI Glossary (Howell, 1939) also quotes the *New International Encyclopedia's* (1915) definition (see above), which like one in Himus's *Dictionary of Geology* recognizes that the widened mouth of a river commonly results from submergence. The application of the term is restricted to the "drowned" valley of a river in the definitions of Finch and Trewartha (1942), as that of the *Encyclopedia Americana* and Webster's second definition cited earlier.

Pritchard (1967), Russell (1967), and others include fiords as estuaries.

Caspers (1967) and Morgan (1967) include delta passes as estuaries, although Guilcher (1963) specifically excludes delta features. De Lapparent (1900) distinguishes an estuary from the delta that may fill it, and Russell (1967) and Steers (1967) point out the difficulty of making a distinction between other types of rivermouth estuaries and delta passes. Bowden (1967) requires only that there is "an inflow of fresh water from land drainage," which presumably might include inflow from fresh-water springs. The 1960 Supplement to the AGI Glossary (Weller, 1960) includes not only "the lower courses of river and small streams (but) drainageways that lead seawater into and out of coastal swamps," returning to the first outmoded definitions of Johnson and the Oxford Dictionary.

Some definitions, such as the general one in the Oxford Dictionary, emphasize the inlet or embayment characteristic without specific restriction to river mouths. Emery and Stevenson (1957) and Russell (1967) regard lagoons and estuaries as a continuous series whose end members alone may be distinguished, but Pritchard (1967) describes bar-built estuaries (lagoons) as a type of estuary. Hedgpeth (1967) considers even a hypersaline lagoon as an estuary, although this would not be included in any common definition. Both Pritchard (1967) and Russell (1967) consider embayments of tectonic origin as types of estuaries regardless of the entry of fresh water required by the *Encyclopedia Britannica* for such embayments.

Ketchum (1951) would include as an estuary any body of water in which river and sea water are mixed, even the open coast, although the open coast is excluded implicitly by common definitions and explicitly by Pritchard (1967).

Hydrodynamics

Almost universally, authors have respected the tidal behavior referred to by the etymology of the term estuary. Russell (1967) explicitly excludes inlets of non-tidal seas, and Pritchard (1967) requires that there be a "free" connection between an estuary and the sea and specifically excludes inlets and lagoons whose communication with the sea is only at high tide. However, Ketchum's (1951) definition, based solely on the dilution of sea water by fresh water, would not exclude inlets of non-tidal seas, and Day (1964) includes "blind" estuaries which are cut off from the sea by bars.

Lee (1840), quoted by the AGI Glossary (Howell, 1939), Defant (1958), and Ippen and Harleman (1966) would include the limits of an estuary, the entire length of a river channel affected by tidal oscillations. A possible more seaward limit to the upper end of the estuarine part of a river mouth might be the limit to which the tides normally cause reversals of flow rather than merely increases and decreases in the velocity of seaward flow. This limit seems not to be used by any authors, although the limit of penetration of salt water, still farther seaward, is used by some (see next section).

A circulation system in which there is a net landward flow of sea water resulting from entrainment in seaward-flowing overlying fresh water, which typically develops in those estuaries in which the fresh-water flow is sufficiently large to maintain a two-layer system (Tully, 1958, Bowden, 1967), has been referred to as an estuarine circulation system, even when recognized in so large a body as the subarctic Pacific (Tully and Barber, 1961). An estuarine circulation system is not established in estuaries without significant vertical salinity gradients, and few authors would consider extension of the term, estuary, to cover the large bodies showing such circulation systems. Such an extension is excluded by Pritchard (1967).

Chemistry

For some authors, notably Ketchum (1951), the dilution of sea water by land drainage is all that is required for definition of an estuary. Most have additional geomorphic or hydrodynamic criteria, as previously discussed, and for some sea-water dilution is not required.

Among those who have sea-water dilution as a necessary but insufficient criterion, there is some variety in definition of the limits of the estuary with respect to the loci of various mixing processes. Mill (1924) considers that only the landward half of the Firth of Forth, in which there exists a distinctive halocline, is a true estuary. The seaward half, in which the salinity is somewhat less than that of the sea and increases gradually seaward, but in which the vertical salinity gradients are negligible, is not. Pritchard (1967) considers that the landward limit of an estuary is the limit to which some significant salinity extends. The adoption of these limits would restrict estuaries to those areas in which "estuarine circulation," defined in the previous section, occurs. However, those who would define an estuary on the basis of its geomorphology and tidal behavior would consider that the entire Firth and Forth is an estuary, that the landward limit of an estuary is the limit of significant tidal action, and that the term, estuaries, includes those inlets in which vertical mixing is sufficiently great to result in essential isohalinity in the vertical throughout.

Pritchard originally considered in 1952 that included among estuaries might be semi-enclosed coastal bodies in which the inflow of fresh water was less than the evaporation and, hence, in which the water that mixes with the sea water is more saline than the sea water. Pritchard called such estuaries inverse or negative estuaries. (Hedgpeth refers to a lagoon in which this condition exists as a hypersaline estuary.) Now however, Pritchard (1967) restricts the term estuary to those bodies in which freshwater inflow predominates over evapotranspiration.

National Estuarine Pollution Study Definition

The term estuary is defined for the National Estuarine Pollution Study by Title II, section 5, subsection (g) (5) of the Clean Water Restoration Act of 1966, Pl 89-753, amending the Federal Water Pollution Control Act (33 U. S. C. 4666 *et seq.*): "The term 'estuary' means all or part of the mouth of a navigable or interstate river or stream or other body of water having unimpaired natural connection with open sea and within which sea water is measurably diluted with fresh water derived from land drainage."

Usage Appropriate in Hawaii

For the purpose of the Hawaiian study, it seems best to include as estuaries both drowned river valleys, such as Nawiliwili Bay on Kauai, and perennial, tide-affected river mouths, such as that of the Wailua River on Kauai. These are equivalent, respectively, to the second and first of the definitions of the Beach Erosion Board (1964). Generally the landward ends of drowned valleys in Hawaii have been filled with sediments, across which the rivers enter the bays. The actual mouths of the rivers are usually restricted by sand bars. The water of many of the drowned-valley bays is essentially sea water except during floods, and the water of many of the tidal rivers is essentially fresh, especially inland toward the limit of the tide. However, typical estuarine salinity and circulation patterns both exist in some of the drowned-valley bays and some of the tidal rivers, and the distinctions in both types between examples with these typical patterns and those without would be quite arbitrary.

The drowned-valley bays range from deep inlets to shallow indentations. The former are sufficiently enclosed to be estuaries, the latter are surely not, but the choice of a minimum bay-length mouth-width ratio to serve as the criterion of an estuary is arbitrary.

The river mouths range from those of perennial streams with large discharges slightly restricted by bars, to those of intermittent streams cut off from the sea except during floods. Only those normally open qualify as true estuaries. Those normally closed may conveniently be called intermittent estuaries (cf. blind estuaries, Day, 1951).

Although Pritchard (1967) equated drowned-valley estuaries and coastal plain estuaries, most of the drowned valleys in Hawaii were cut into the bedrock of the volcanic shields and the estuaries in them are bounded laterally by high ridges of lava rather than coastal-plain sediments. Pearl Harbor, Oahu, however, is a true coastal-plain estuary, occupying a drowned valley eroded into sediments.

Although the fresh water discharge from the major rivers inhibits the growth of corals, some of the drowned-valley estuaries have partial coral-reef bottoms and many have slight restrictions of their mouths by fringing reefs. An example is Kahana Bay, Oahu.

Kaneohe Bay, Oahu is unique, being the result of the coalescence of several drowned valleys and being effectively isolated from ocean waves by an extensive coral reef. It is, therefore, a lagoon as well as an estuary.

There are no fiords in Hawaii, and no semi-enclosed bays of tectonic origin.

Some coastal spring channels raise problems. The Wailoa River, entering Hilo Bay, is clearly an estuary being tidal, brackish, and of increasing salinity seaward throughout the half mile in which it has perennial flow due to spring discharge. The Keaukaha springs, also in Hilo, are identical in tidal response, fresh water supply, and mixing conditions, but they discharge through the irregular terrain of a fresh pahoehoe lava flow rather than a channel partly confined by sediments. Probably their channels too should be considered as estuaries.

In conclusion, it appears that a definition of estuary appropriate to Hawaiian needs may be:

1. A bay, such as a drowned river valley, that receives fresh water discharged from the land.

2. The tidal portion of the mouth of a stream.

This compound definition, similar to that of the Beach Erosion Board (1964), is slightly more inclusive than that of the National Estuarine Pollution study in that it does not require navigability (although a skiff could navigate all but the shallowest and narrowest of estuaries included) and in that it includes those drowned valleys or seaward parts of drowned stream valleys whose waters are not measurably diluted by fresh water.

Contract no. 19-12-446 of the Federal Water Pollution Control Administration with the University of Hawaii, 29 June 1968, for the *Study of Estuarine Pollution in the State of Hawaii,* specifies that the study shall include the following five major estuaries:

Kahului Harbor, Maui
Hilo Bay, Hawaii
Nawiliwili Bay, Kauai
Pearl Harbor, Oahu
Kaneohe Bay, Oahu

Of these five, Nawiliwili, Pearl Harbor, and Kaneohe clearly qualify as natural estuaries according to the definition suggested. It is questionable whether any part of Hilo Bay would have qualified prior to construction of the breakwater, although the degree of its enclosure by the natural reef and the quantity of fresh water supplied by the Wailuku and Wailoa Rivers might have been sufficient. The mouths of the two rivers are clearly estuaries. The additional restriction and confinement of mixing afforded by the breakwater should now be sufficient to qualify Hilo Harbor as an estuary. Kahului Harbor may well not qualify, even with its breakwaters, owing to an insufficient fresh-water supply. It is entered by no streams or significant springs but only storm drain discharge. It is, in spite of this, be included in this FWPCA sponsored study.

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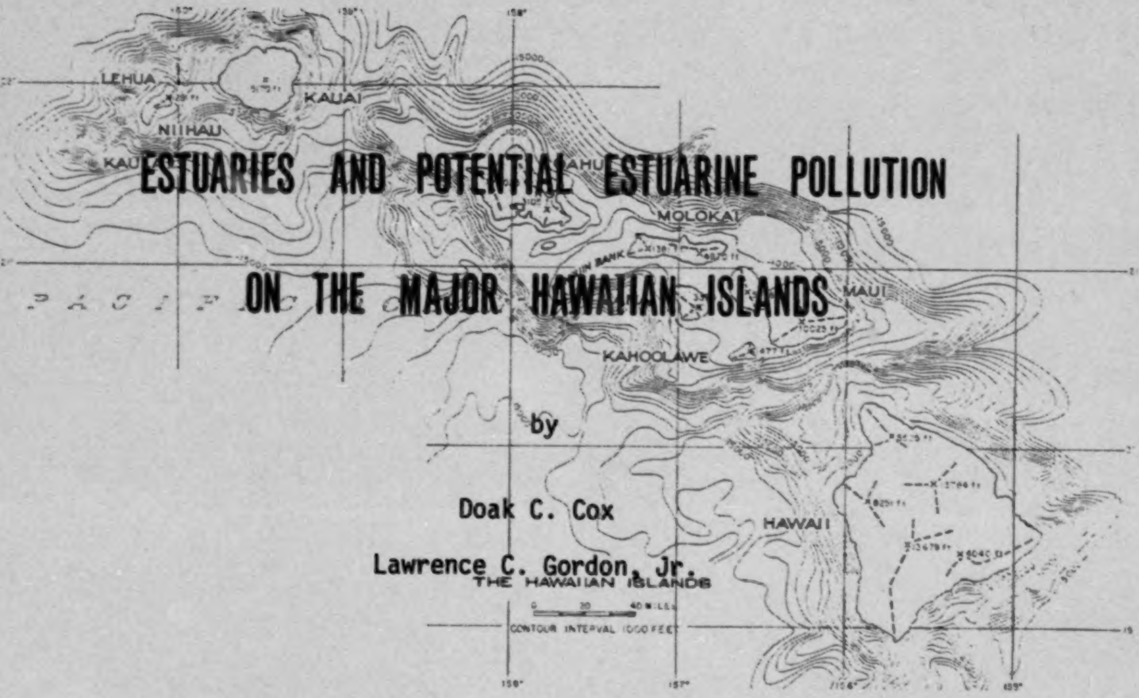

ESTUARIES AND POTENTIAL ESTUARINE POLLUTION ON THE MAJOR HAWAIIAN ISLANDS

by

Doak C. Cox

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INTRODUCTION

A discussion of estuaries and estuarine pollution in Hawaii must present great contrasts. The largest island, Hawaii, has very few estuaries because most of its coasts are of such recent volcanic origin. Some of the smaller islands have no significant estuaries because they are either too dry to have perennial streams or to have been deeply eroded by streams. However, on the island of Kauai which is well-watered and deeply eroded, there are 15 streams which have significant tidal lower reaches and 11 well-marked bays resulting from drowning of stream valleys excavated in volcanic terrain. Pearl Harbor, on Oahu, is a true coastal plain estuary, resulting from the drowning of a stream valley excavated in coastal-plain sediments. Kaneohe Bay, also on Oahu, is a sort of compound estuary-lagoon.

Some of the estuaries on the islands are fed by streams draining land in near-wilderness conditions. These little used estuaries are subject to rapid and efficient flushing and the chemical and bacterial quality of their waters is probably as good as their sparkling appearance suggests. Other estuaries receive a combination of urban, domestic, industrial, and agricultural wastes; their flushing is restricted; and their waters have become objectionable with respect to color, odor, bacterial quality, and chemical content.

Scope of the Project

The statewide study of estuarine pollution reported here was intended to collate and summarize existing information on pollutants, pollution, and pollution trends. It has, unfortunately, proved difficult to obtain definitive information on the pollution of either relatively unpolluted or relatively polluted estuaries in Hawaii. Until recently, pollution seems to have been either of little concern or considered beyond control. Because information on the actual nature and extent of pollution is scanty and incompletely collected this study presents, for the most part, not definitive or quantitative statements on the nature and extent of estuarine pollution but indications based on limited observation, on information casually noted in studies intended for other purposes, as aspects of the usages of estuaries and the drainage basins tributary to them that introduce potentials of pollution of various sorts.

The tables showing land and estuarine use, considered together with the discussion in the next section on land use and potential estuarine pollution, may be regarded as checklists of possible pollution, the actual existence and extent of which is subject to field confirmation.

Such data on actual levels of pollution as have been found are discussed in the sections on each of the major estuaries, together with geographic factors bearing on the pollution problem.

Field work in the statewide project reported here has been restricted to reconnaissance of particular problem areas on Oahu and an initial and at least one follow-up visit to each of the other major islands.

The basis of this report on the statewide study, other than the limited results of this field work, involved previous field data, published information, and interviews with personnel in concerned agencies.

Various agencies, such as the U. S. Army Corps of Engineers, the Department of Health, and consulting engineer firms were contacted to see what kind and how much data they had available dealing with estuarine pollution. A list of streams and estuaries for each island and the potential sources of pollution of these water bodies was drawn up. A bibliography covering many aspects of estuarine pollution (biological, engineering, water resources, sugar waste studies, etc.) has been compiled and is published as an appendix to this volume.

Acknowledgements

A large number of persons in federal agencies, state agencies, and private employment have been of assistance in this study.

The assistance of the following persons should be especially recognized: Mr. Shinji Soneda, Executive Officer, Mr. Peter Sakai, and Mr. James Nakahara of the Water Pollution and Environmental Health Division, Department of Health, State of Hawaii; Mr. Donald B. Mausshardt, Director, and others in the Pacific Islands Basin Office of the Federal Water Pollution Control Administration in Honolulu; and Miss Janet Bell, Librarian, Hawaiiana and Pacific Section of Sinclair Library, University of Hawaii.

GENERAL GEOGRAPHY

Geology

The Hawaiian Islands (Fig. 1) are the tops of at least 16 basalt shield volcanoes rising from the floor of the Pacific 15,000 to 18,000 feet below sea level to elevations ranging from a few hundred feet on the island of Kaula to nearly 14,000 feet at the summit of Mauna Loa and Mauna Kea on the island of Hawaii (Stearns, 1967).

Two of the volcanoes, Kilauea and Mauna Loa on Hawaii, are still in a very active period of construction. Two others, Hualalai on Hawaii and Haleakala on Maui have erupted in historic times. Others of the volcanic shields have been deeply eroded by both streams and the sea through long periods of inactivity, but post-erosional renewed volcanic activity has greatly modified the erosional topography of some of these. The island of Kaula has been reduced by erosion to a mere pinnacle. It is uninhabited and will not be further considered in this report.

Isostatic sinking of the older islands has resulted in the drowning of major valleys on the older islands. However, most of these valleys have subsequently been at least partially refilled by sediments. Glacial changes in sea level have resulted in the drowning of the lower portions of smaller valleys within major valleys and elsewhere to form estuaries.

Although the islands are near the northern limits of coral reef development, there are extensive coral reefs along some of the shores of the older islands and the protection afforded by coral reefs has permitted the development of sedimentary coastal plains on some coasts of the older, eroded volcanoes.

Climate

During the summer season, from May through September, the weather of the islands is controlled predominantly by the northeast trade winds. Major storms associated with the passage of cold fronts and cyclonic circulations occur principally during the winter months, October through April. Orographic effects affect the distribution of storm rain and especially the distribution of trade-wind rain. Peak annual rainfalls, in excess of 200 inches on several of the mountains and in excess of 400 inches on Kauai and West Maui, occur in the summit areas of the mountains that are less than 6,000 feet in height and at an elevation of about 3,000 feet on the windward sides of the higher mountains that extend above the layer of moisture-laden air and the trade-wind inversion associated with the trade winds. In the lee of larger mountain masses, rainfall is also associated with local land-and-sea air circulation. Rainfall is highly seasonal at high elevations and in leeward lowland areas where storm rainfall predominates, but not so highly seasonal in areas where trade-wind rainfall predominates (Blumenstock, 1961).

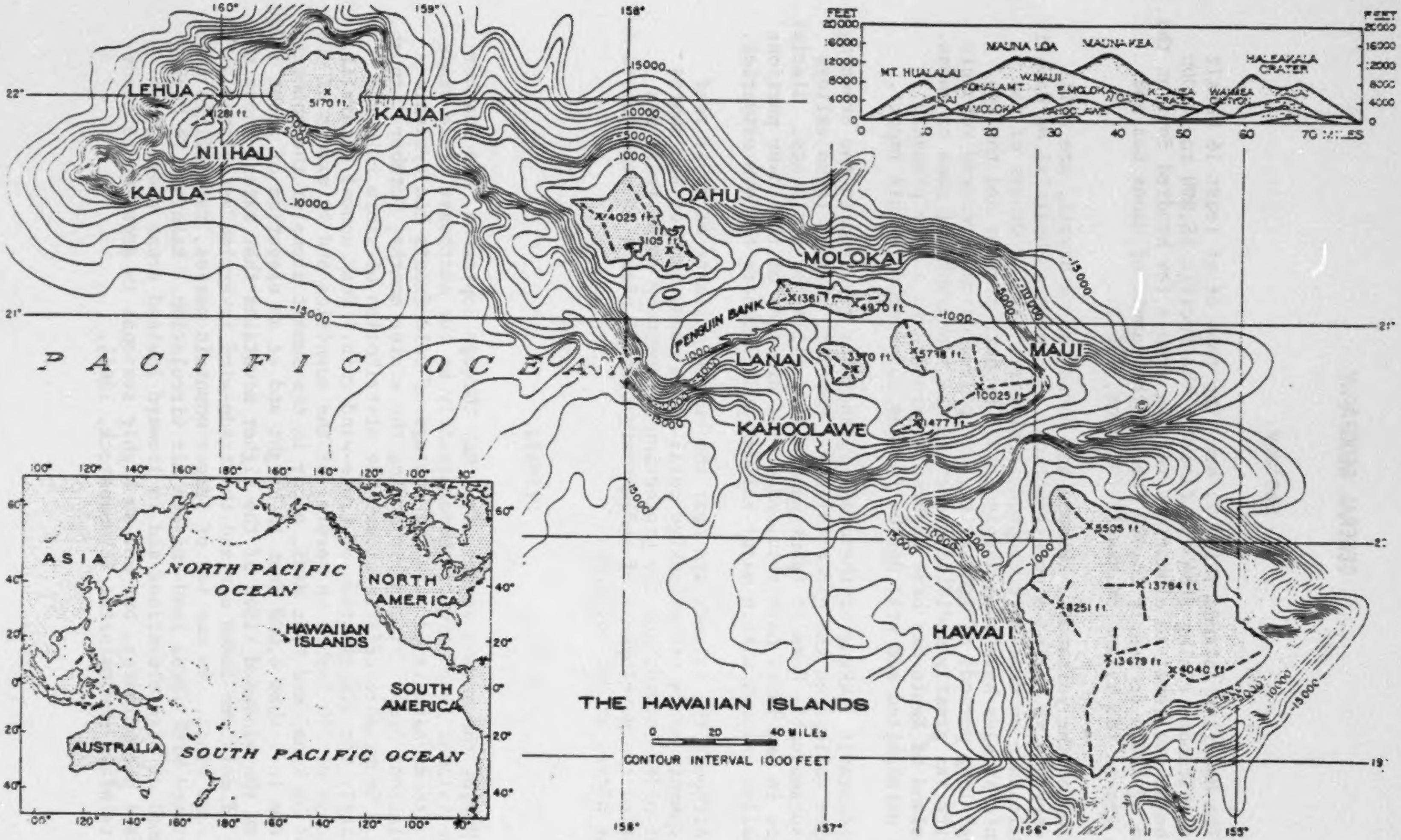


FIGURE 1. THE HAWAIIAN ISLANDS (FROM STEARNS, 1967).

The range of normal temperatures of near-sea-level areas is indicated by the records for Lihue Airport on the windward coast of Kauai, where the monthly mean temperatures range from about 70° to 78° F, and for Honolulu on the leeward coast of the Koolau Range of Oahu, where monthly mean temperatures range from about 72° to 79° F. Average daily maxima and minima for the coldest and warmest months for these places are shown in Table 1.

TABLE 1. MEAN HAWAIIAN COASTAL TEMPERATURES IN °F

	LIHUE AIRPORT, KAUAI	HONOLULU, OAHU
WARMEST MONTH	AUGUST	SEPTEMBER
MEAN	78.1°	78.5°
MEAN DAILY MAX.	83.3°	82.9°
MEAN DAILY MIN.	72.9°	73.7°
COLDEST MONTHS	JANUARY-FEBRUARY	JANUARY-FEBRUARY
MEAN	70.1°	72.0°
MEAN DAILY MAX.	77.6°	76.7°
MEAN DAILY MIN.	62.6°	67.2°

The infiltration capacity of the rocks and soils over most of the Hawaiian Islands is very high. Ground-water tables are generally very deep below the surface in most of the island areas and the streams are short and steep, hence stream discharges are in general very flashy (Hawaii Water Authority, 1959). There are generally no perennial discharges from areas of low rainfall or areas of fresh lavas. Substantial dry weather flows are derived only from areas of lower than normal infiltration capacity and flatter than normal slopes or from springs.

Oceanography

The Pacific north equatorial current results in a generally westerly or northwesterly flow in the vicinity of the islands, varying, however, from west-southeast to north-northwest. The velocity ranges from less than 0.1 knot to more than 1 knot with an average slightly exceeding half knot. Major eddies are common downstream from the islands. Superimposed upon the general drift are tidal currents whose velocities in nearshore areas are commonly on the order of a knot but locally at sharp headlands amount to several knots (Laevastu, Avery, and Cox, 1964; Wyrtki, *et al.*, 1967).

The ocean tides in the vicinity of the Hawaiian Islands are of mixed type with maximum ranges of about three feet.

The average temperature of the surface in the open ocean around Hawaii ranges from a minimum of 74° F in late March or early April through a maximum of 79° or 80°F in late September or early October (Blumenstock, 1961).

LAND USE AND POTENTIAL ESTUARINE POLLUTION

In order to identify elements of potential estuarine pollution, the various estuaries together with various water-development and land-use factors that appear to have some importance either as sources of possible pollutants, limitations of pollution, or controls on the consequences of pollution have been tabulated for each of the major islands. The factors identified are discussed very briefly below. For each factor, the symbol used in the tables is indicated.

It would at present be premature to generalize on the overall importance of any of the water-development and land-use factors, and it is difficult to evaluate their actual effects on most estuaries. However, the tables will not only serve as guides to the continuing work in the project but should be useful in other estuarine pollution investigation that may be in progress.

Water Development

	Symbols used in tables
Irrigation diversion: Water diverted, without significant storage,for irrigation often outside the drainage basin of the diversion. Low-water flows in the estuaries are greatly reduced or even eliminated, flood flows remain essentially unchanged. Flushing of stream-mouth estuaries may be greatly restricted. Stream-mouth sand bars may be more extensively developed than under natural conditions.	*I*
Power diversion: Water is diverted for hydroelectric power development and returned to the same stream; no special effect on estuarine conditions.	*E*
Storage: There is significant storage of water in the stream course together with diversion; even flood flows are reduced.	*S*

Agricultural Development

Sugar cane cultivation: Possible source of enrichment in fertilizer components such as nitrates and potash, especially through ground water, and possible source of herbicides, although many such chemicals are found to be highly adsorbed and degraded in the soil. Accelerated sediment yield may result from loss of cover from harvest until the vegetative canopy closes in. Erosion is, however, limited by furrowing, especially in irrigated fields.	*S*

	Symbols used in tables
Pineapple cultivation: Possible source of enrichment in fertilizer components, herbicides, and other pesticides. Sediment yield is possibly accelerated although erosion is controlled by quasi-contour planting, grassed drainways, etc.	*P*
Taro cultivation: Probably minor pollution contributions.	*T*
Banana cultivation: Pollution importance unknown and probably minor.	*B*
Ranching: Probably minor pollution contribution where animal population concentration is small. Important source of bacterial pollution, nitrates, etc., where the concentration is high as in feed lots and dairy pens.	*R*
Miscellaneous: Pollution contribution depends on nature and concentration of use.	*M*

Industrial Development

Sugar factory: Mud, cane trash, nutrients, and bacterial pollution from cane cleaner, excess bagasse, waste sugars, and other soluble organics. (A detailed characterization is given in FWPCA, in preparation.)	*S*
Pineapple cannery: Pineapple wastes, soluble organics including organic acids. (A detailed characterization is given by Kumagai, 1965.)	*P*
Petroleum refinery: Refinery wastes, sulfides and sulfates, phenols, caustics.	*R*
Thermal power plant: Heated water.	*E*
Quarry: Accelerated sediment yield.	*Q*
Miscellaneous	*M*

Urban Development

Sanitary-sewered urban areas on estuary or within two miles upstream on tributaries: Augmented flood discharges. Trash, detergents, pollutants from minor industry. Accelerated sediment production in new subdivisions. Nitrates, phosphates, and bacterial contamination.	*S*

	Symbols used in tables
Urban areas served by cesspools and septic tank-drain field systems on estuary or within two miles upstream on tributary: Pollutants listed for sewered urban areas plus high nutrient concentrations and bacterial contamination from cesspool overflows or other inadequacies.	*C*

Estuary Development

Commercial or military harbor: Fuel oil and lubricating oil spills. Bilge discharges. Ship sewage. Miscellaneous industrial pollution. Cargo spills.	*H*
Small-boat harbor: Small-boat sewage. Miscellaneous trash.	*S*
Sewer outfall -- raw sewage: Raw sewage, bacterial contamination, organic wastes, high nutrient concentrations.	O_R
Sewer outfall -- primary treatment: Bacterial contamination, organic waste, high nutrient concentrations.	O_P
Sewer outfall -- secondary treatment: High nutrient concentrations.	O_S
Pond fishery	F_P
Bait fishing	F_B*
Shell-fishing	F_S*
Swimming, boating, and other recreational uses	*R**

*Some fishing, swimming, and boating are common in practically all Hawaiian estuaries. Only usages significantly more intensive than normal are indicated in tables.

WATER QUALITY STANDARDS

Definitions and Classification of Water Uses

Pursuant to the Federal Water Quality Act of 1965 and Act 163, Session Laws of Hawaii, 1965, the Director of Health of the State of Hawaii was empowered to divide the waters of the State into areas, and to adopt standards of water quality for each area after conducting public hearings. The hearings were held in 1966 and 1967 (Department of Health, 1966 a, b, 1967 a, b, c, d), and in 1968 the area designations and water quality standards were adopted in the Regulations of the Department of Health (Department of Health, 1968).

Pertinent to the estuaries of the islands are the following definitions and classifications in the regulations:

> "Section 2. DEFINITIONS.
>
> 'Near shore water' means all coastal waters lying within a defined reef area, all waters of a depth less than 10 fathoms, or waters up to a distance of 1000 feet off-shore if there is no defined reef area and if the depth is greater than 10 fathoms.
>
> 'Off-shore waters' means all coastal waters defined for 'near-shore waters.'
>
> 'Coastal waters' includes 'near-shore waters,' 'off-shore waters' and those brackish waters, fresh waters and salt waters that are subject to the ebb and flow of the tide.
>
> "Section 3. CLASSIFICATION OF WATER USES.
>
> A. Classification of Coastal Water Uses
>
> Coastal waters are classified in accordance with the uses to be protected in each class as follows:
>
> 1. *Class AA waters*
>
> The uses to be protected in this class of waters are oceanographic research, propagation of shellfish and marine life, conservation of coral reefs and wilderness areas and aesthetic enjoyment.
>
> It is the objective of this class of waters that they remain in as nearly

their natural, pristine state as possible with an absolute minimum of pollution from any source. To the extent possible, the wilderness character of such areas shall be protected. No zones of mixing will be permitted in these waters.

The classification of any water area as Class AA shall not preclude other uses of such waters compatible with these objectives and in conformance with the standards applicable to them.

2. *Class A waters*

The uses to be protected in this class of waters are recreational, including fishing, swimming, bathing and other water-contact sports and aesthetic enjoyment.

It is the objective for this class of waters that their use for recreational purposes and aesthetic enjoyment not be limited in any way. Such waters shall be kept clean of any trash, solid materials or oils and shall not act as receiving waters for any effluent which has not received the best practicable treatment or control compatible with the standards established for this class.

3. *Class B waters*

The uses to be protected in this class of waters are small boat harbors, commercial, shipping and industrial, bait fishing and aesthetic enjoyment.

It is the objective for this class of waters that discharges of any pollutant be controlled to the maximum degree possible and that sewage and industrial effluents receive the best practicable treatment or control compatible for the standards established for this class.

The Class B designation shall apply only to a limited area next to boat docking facilities in bays and harbors. The rest of the water area in such bay or harbor shall be Class A unless given some other specific designation in Section 5.

Classification of Estuaries

All of the estuaries of the Hawaiian Islands, as defined in this report, are, by the above definitions, included as coastal waters. The deepest part of the entrance to Hilo Harbor is ten fathoms in depth, and some of the bay estuaries of Molokai and of the northeast coast of East Maui may possibly have maximum depths of as much as ten fathoms and be more than 2000 feet in width at their mouth. Hence, very small sections of a few estuaries may be included as *offshore waters*. Almost the entire extent of bay estuaries is, however, included as *nearshore waters*. Although it is not clear from the definition of *nearshore waters* whether river-mouth estuaries are included, in them, it appears from the definition of *coastal waters* that river-mouth estuaries are in a third, unnamed, sub-category of coastal waters, constituted by *those brackish waters, fresh waters and salt waters that are subject to the ebb and flow of the tide*.

It may be noted in passing that the definition given of coastal waters could literally include basal ground waters, which ordinarily in Hawaii have a tidal response, as well as bodies of fresh, brackish, and salt surface water fed by such basal ground water, even if these bodies have no surface connection with the sea. It is doubtful that this inclusion was intended.

As the three classes of coastal water areas have been defined in Section 5 of the Regulations (Department of Health, 1968), the several estuaries of the Islands, to be described in subsequent sections, are distributed among them as shown in Table 2.

Pertinent Water Quality Standards

Section 6 of the Regulations (Department of Health, 1968) establishes standard pertinent to water quality in the three classes of estuarine waters which are condensed in Table 3.

TABLE 2. COASTAL WATER CLASSES OF HAWAIIAN ESTUARIES.

ISLAND	AA	A	B
KAUAI	HANALEI BAY	WAIMEA RIVER	HANAPEPE BAY, PORT ALLEN AND SMALL BOAT HARBOR
	WAINIHA BAY	HANAPEPE RIVER	NAWILIWILI BAY
		HANAPEPE BAY, PART NOT IN PORT ALLEN AND SMALL BOAT HARBOR	WAILUA RIVER SMALL BOAT HARBOR
		WAHIAWA BAY	
		LAWAI STREAM AND BAY	
		HULEIA STREAM	
		HANAMAULU STREAM AND BAY	
		WAIALUA RIVER ABOVE SMALL BOAT HARBOR	
		WAIAKEA AND MOIKEHA CANALS	
		KAPAA STREAM	
		ANAHOLA STREAM	
		MOLOAA BAY	
		KILAUEA STREAM AND BAY	
		KALIHIWAI STREAM AND BAY	
		HANALEI RIVER	
		WAIOLI AND WAIPA STREAMS	
		LUMAHAI RIVER	
		WAINIHA RIVER	
OAHU	PEARL HARBOR, PART OF WEST LOCH	KALIHI CHANNEL AND KEEHI LAGOON, ALL PARTS NOT IN MARINA AREAS (EXCEPT THAT KALIHI SHIP CHANNEL MAY BE INCLUDED WITH HONOLULU HARBOR IN CLASS B)	PEARL HARBOR, ALL EXCEPT THE PART IN CLASS AA
	KANEOHE BAY, DESIGNATED MAJOR CENTRAL PORTION AND SMALL AREAS AT SOUTHEAST END OF BAY	ALA WAI CANAL	KEEHI LAGOON, MARINA AREAS
	KAHANA BAY	KUAPA POND	HONOLULU HARBOR
	WAIALUA BAY	WAIMANALO STREAM	ALA WAI SMALL BOAT HARBOR AND KEWALO BASIN
		KAELEPULU STREAM AND KAWAINUI CANAL	KANEOHE BAY, STATE AND KMCAS SMALL BOAT HARBORS AT SOUTHEAST END OF BAY
		KANEOHE BAY, RIM OF BAY AND MOST OF SOUTHEAST END OF BAY EXCLUDING SMALL BOAT HARBORS AND SMALL AREAS DESIGNATED CLASS AA	HALEIWA SMALL BOAT HARBOR
		KAHANA STREAM	
		WAIMEA STREAM AND BAY	
		LOKO EA AND ANAHULU RIVER	
		KAIAKA BAY AND PAUKAUILA AND KIIKII STREAMS	
MOLOKAI	PELEKUNU BAY	HALAWA STREAM AND BAY	
	FISH PONDS?	FISH PONDS?	
MAUI	KAHAKULOA BAY	MALIKO BAY	KAHULUI BAY
	BAY ESTUARIES ON NORTHEAST COAST OF EAST MAUI	HONOKOHAU BAY	
		HONOLUA BAY	
HAWAII		WAILUKU AND WAILOA RIVERS	HILO HARBOR
		WAIPIO STREAM	
		POLOLU STREAM	

TABLE 3. WATER QUALITY STANDARDS PERTINENT TO HAWAIIAN ESTUARIES.

SUBSTANCE		AA	A	B
A. BASIC				
1. SETTEABLE MATERIALS FORMING OBJECTIONABLE DEPOSITS		0	0	0
2. FLOATING DEBRIS, OIL, SCUM, ETC.		0	0	0
3. SUBSTANCES PRODUCING OBJECTIONABLE		0	0	0
4. COLOR, ODOR, TASTE, OR TURBIDITY		0	0	0
5. SUBSTANCES, CONDITIONS, OR COMBINATIONS PRODUCING UNDESIRABLE AQUATIC LIFE		0	0	0
6. SOIL FROM CONTROLLABLE ACCELERATED EROSION		0	0	0
B. SPECIFIC				
1. MICROBIOLOGICAL				
A. COLIFORM BACTERIA (/100 ML)				
MEDIAN	≤	70	1000	
UPPER DECILE	≤		2400	
MAXIMUM	≤	230		
B. FECAL COLIFORMS				
30-DAY MEAN	≤	200	400	
30-DAY UPPER DECILE	≤	400	1000	
2. PH				
DEPARTURE FROM NATURAL	≤	0.5	0.5	0.5
MAXIMUM EXCEPT FROM NATURAL CAUSES	≤	8.5	8.5	8.5
MINIMUM EXCEPT FROM NATURAL CAUSES	≤	8.0	7.0	7.0
(EXCEPT FRESH TIDAL WATER)	≥	7.0		
3. NUTRIENTS (MG/L)				
TOTAL P	≤	0.020	0.025	0.030
TOTAL N		0.10	0.15	0.20
4. DISSOLVED OXYGEN (MG/L)				
(EXCEPT FROM NATURAL CAUSES)	≤	6.0	5.0	4.5
5. TOTAL DISSOLVED SOLIDS, SALINITY AND CURRENTS				
TDS DEPARTURE FROM NATURAL (% OF NATURAL FLUCTUATION)		10		
TDS (MG/L)	≥	28000		
6. TEMPERATURE (^{o}F)				
DEPARTURE FROM NATURAL	≤	1.5	1.5	1.5
7. TURBIDITY				
SECCHI DISK EXTINCTION COEFFICIENT, DEPARTURE FROM NORMAL (%)	≤	5	10	20
8. RADIONUCLIDES				
(MPC_n VALUES BY NBS)	≤	1/30	1/30	1/30
(CONCENTRATION)	≤	USPHS VALUES FOR DRINKING WATER		
(CONCENTRATION CAUSED IN HARVESTED ORGANISMS)	≤	FEDERAL RESOURCE COUNCIL RECOMMENDED LIMITS		

NIIHAU

The island of Niihau consists of the remnant of a basalt volcanic shield greatly reduced, mainly by marine erosion, but extended by post-erosional volcanics and sediments (Stearns, 1947). The highest elevation is less than 1,300 feet. Hence, rainfall is low on the island. There are no perennial streams, no very deep valleys, and no true estuaries on the island.

There is a small blind estuary at the mouth of the intermittent Keanauhi Stream, and some of the dozen lakes and plazas on the coastal plain are essentially lagoons isolated from the sea by beach ridges on dunes.

KAUAI

Kauai (Fig. 2) is geologically the most complex of the Hawaiian Islands (Macdonald, Davis, and Cox, 1960). Except along the dry western coast, the original flanks of the volcanic shield have been greatly reduced by erosion toward a base level far below the present sea level. On the eroded topography has been piled a greater mass of post-erosional volcanics than on any other Hawaiian volcano. The original shield-forming rocks of the volcano meet the present shores only on the cliff coast at the northwest and southeast of the island. Most of the southeast and north coast are formed by the post-erosional volcanics, although there are local sedimentary coastal plains along these coasts and a large sedimentary coastal plain at the southwest coast.

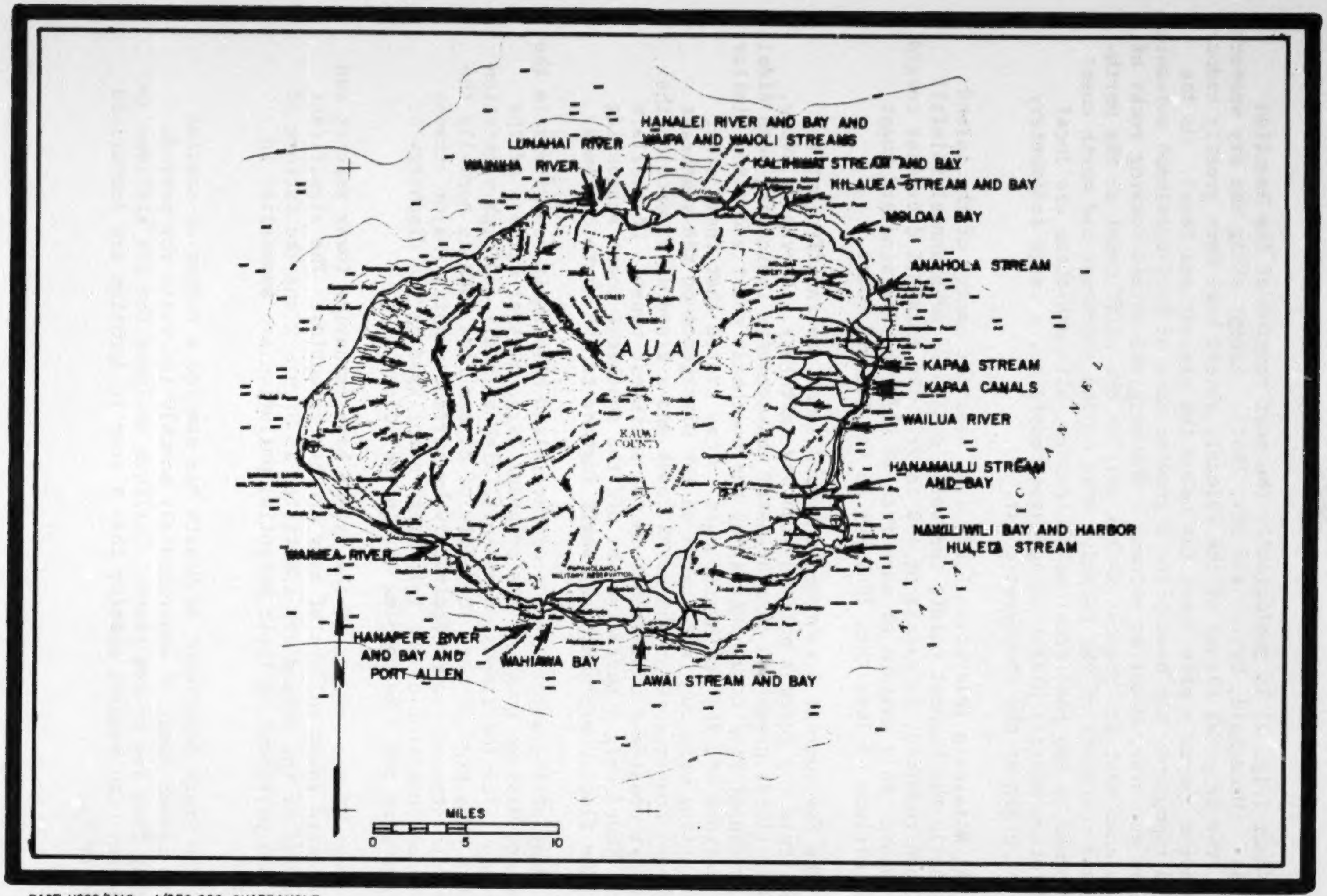
At Waialeale (elevation 5,080 ft), near the center of the island and nearly the highest point, the world's highest mean annual rainfall has been recorded, in excess of 450 in/yr. The rainfall decreases toward the coasts, to a maximum of more than 40 in/yr on the windward coast and a minimum of less than 20 in/yr on the leeward coast.

The few current measurements around Kauai are insufficient to demonstrate the current pattern with any certainty. Laevastu, Avery, and Cox (1964) presented current-meter measurements indicating both tidal and permanent flow components along the southeast coast and cited similar observations off the southwest coast. They stated that their other observations were consistent with an ebb divergence on the southeast coast and convergence on the north coast and a flood divergence on the northeast coast and convergence on the southwest coast. Chamberlain (1965) found only a northward set off the southwest coast suggesting that the flood convergence may shift further to the north at times.

Many of the major streams of the island have their headwaters in the dense and massive rocks of the original large central caldera of the volcano. The low slopes, deep soil, high rainfall, and high vegetation in this area provide more stability of stream flow than is normally the case with streams fed predominantly by surface runoff. Major streams on the eastern side of the island are stabilized by the discharge of springs from the dike complex within the volcano.

Most of the streams of the island have estuarine lower reaches and the drowned lower valleys of many are bay estuaries. The significant estuaries of the island are identified in Figure 2 and the factors of land use pertinent to their potential pollution are summarized in Table 4.

The State Department of Health has sampled a number of coastal waters around Kauai at approximately monthly intervals for periods ranging from one to ten years. Coliform analyses for the stations on estuaries with records greater than a year in duration are summarized in Table 5.



BASE: USGS/AMS 1/250,000 QUADRANGLE

FIGURE 2. ESTUARIES OF THE ISLAND OF KAUAI.

TABLE 4. ESTUARIES OF KAUAI AND THEIR POTENTIAL POLLUTION.

ESTUARY SYSTEM	BAY ESTUARY	STREAM ESTUARY	WATER DEVELOP-MENT	AGRICULTURAL DEVELOPMENT	INDUSTRIAL DEVELOPMENT	URBAN DEVELOP-MENT	ESTUARY DEVELOPMENT
WAIMEA		WAIMEA R	I, E 1)	R, S, T		C	
HANAPEPE (PORT ALLEN)		HANAPEPE R	I	S, T, R		C	
	HANAPEPE				E	C, S	H, S, R (O_R) 2)
WAHIAWA	WAHIAWA	SEE FOOTNOTE 3)	S	S, R			
LAWAI	LAWAI	LAWAI STR	I	S, R			
NAWILIWILI		HULEIA STR	I	S, R			F_P
	NAWILIWILI		I	S	S, M 4)	C, S	H, F, R O_S
HANAMAULU (AHUKINI)		HANAMAULU STR	I	S		C	
	HANAMAULU						R
WAILUA		WAILUA R	I, E	S, R		C	S, R
KAPAA		KAPAA CNL		S, P	P	C	
		KAPAA STR		S, P, R		C	
ANAHOLA		ANAHOLA STR	I	S, R		C	
	ANAHOLA						R
MOLOAA	MOLOAA	MOLOAA STR	I	S, R			
KILAUEA		KILAUEA STR	I	S, R			
	KILAUEA				Q		
KALIHIWAI		KALIHIWAI STR	I	S, R			
	KALIHIWAI						R
HANALEI		HANALEI R	I	T, R			R
		WAIOLI STR		R			
		WAIPA STR		R			
	HANALEI					C	R, F_B
LUMAHAI		LUMAHAI R		R			
WAINIHA		WAINIHA R	E	R, T			
	WAINIHA					C	

1) REFER TO PAGES 18 - 20 FOR THE KEY TO THESE SYMBOLS.

2) THE ELEELE SEWER OUTFALL IS OUTSIDE THE PORT ALLEN BREAKWATER.

3) THE FORMER WAHIAWA STREAM-MOUTH ESTUARY IS LARGELY FILLED WITH SEDIMENTS RESULTING FROM THE COLLAPSE OF A LARGE HYDRAULIC FILL DAM THAT WAS UNDER CONSTRUCTION IN THE MOUNTAINS IN THE 1930'S. THE BEACH SAND HAS A HIGH CONTENT OF TERRESTIAL SEDIMENTS AND THE WATER IN THE BAY IS ALSO STILL MUDDY.

4) THE CANE CLEANER WASTE WATER FROM THE LIHUE MILL IS PARTLY USED FOR IRRIGATION. EXCESS IS DISPOSED OF TO THE OPEN COAST A MILE OR SO NORTH OF NININI POINT AT THE NORTHERNMOST POINT OF NAWILIWILI BAY.

TABLE 5. COLIFORM ANALYSES FOR KAUAI ESTUARIES. ANALYSES BY DEPARTMENT OF HEALTH.

			MPN/100 ML			
	PERIOD	NO. OF SAMPLES	MINIMUM	MEDIAN	UPPER DECILE	MAXIMUM
WAIMEA RIVER MOUTH	1951-63	34	60	2400	>7,000	>7,000
HANAPEPE RIVER MOUTH	1959-63	34	60	2400	7,000	>7,000
NAWILIWILI PIER 1	1959-63	32	0	230	2,400	7,000
KALAPAKI	1959-69	66	6	620	7,000	24,000
HANAMAULU BEACH AT COUNTY PARK	1959-69	67	7	620	7,000	>24,000
WAILUA RIVER MOUTH	1959-69	68	7	2400	7,000	24,000
WAILUA BEACH AT COUNTY PARK	1959-69	68	0	62	2,400	>7,000
WAIAKEA CANAL	1959-63	35	? 23	2400	7,000	>7,000
MOIKEHA CANAL	1959-63	34	<23	230	2,400	7,000
KAPAA BEACH AT COUNTY PARK	1959-69	69	0	23	2,400	>7,000
ANAHOLA RIVER MOUTH	1959-63	33	<23	230	>7,000	>7,000
ANAHOLA BEACH AT COUNTY PARK	1959-69	69	0	0	62	620
HANALEI BEACH AT COUNTY PARK	1959-69	67	0	620	7,000	>7,000
HANALEI BEACH AT LANDING	1959-69	68	0	620	7,000	24,000

Waimea River

The Waimea River (Fig. 3) of southwestern Kauai has an estuarine lower course nearly two miles in length. The upper end of the estuary has two arms, the western one being the Waimea River itself and the eastern, the Makaweli River, its major tributary. The valley of the Waimea River above the confluence follows a fault scarp between the oldest series of flank lava flows to the west and a later series of lavas to the east. The valley of the Makaweli River lies between the somewhat later laval and post-erosional lavas to the east. Both the Waimea and the Makaweli Rivers have flood plains with widths of about 1,000 feet. Below the confluence, the flood plain has a width of about 2,000 feet.

The natural mean flow of the Waimea River is about 132 mgd, that of the Makaweli about 91 mgd and the sum, therefore, is about 223 mgd (Davis, 1960). Much of the waters from both rivers is, however, diverted upstream of the estuary for irrigation. Mean diversions are about 55 mgd for the Waimea and 46 mgd for the Makaweli, leaving a mean flow through the estuary of about 122 mgd. Two small hydroelectric plants in the upper valley of the Waimea divert water from the Waimea River but return the water to the river and hence have no influence on the flow downstream. The minimum natural flow through the estuary would probably be about 20 mgd. However, during dry weather practically all of the water from both rivers is diverted so that the discharge through the estuary during dry summer months is only a few million gallons per day under present conditions. The lowest ditch on the eastern bank of the upper estuary, which carries water diverted from the Waimea River, follows the alignment of a prehistoric ditch with unique stone work traditionally attributed to the Menehune (legendary little folk).

The town of Waimea occupies the flood plain of the lower Waimea and the adjacent coastal plain. A flood-control dike has been erected on the western bank of the river to protect the town.

A sand bar generally developing very nearly across the mouth of the Waimea under dry summer conditions is generally removed by the winter floods.

The headwaters of both the Makaweli and the Waimea are in state park and forest reserve lands. Lands west of the Waimea at lower elevations are in sugar cane but these lands drain to the west. The lower lands between the Waimea and the Makaweli are in low-density cattle-ranch use. The lower lands east of the Makaweli are in sugar-cane fields from which some drainage reaches the Makaweli. The major potential source of pollution, therefore, is the town of Waimea itself, which is now served by cesspools. Tight soils and dense rocks are reported to impede cesspool drainage in some areas but in general the underground drainage is good. Some of this drainage may reach the river contributing at least nutrients to it.

By reason of its tidal behavior, Waimea River must be in Class A of coastal waters. However, analyses of total coliform concentrations by the Department of Health in the period 1959-63 (Table 5) have a median of 2,400 MPN/100 ml and an upper decile value of >7,000 MPN/100 ml, both of

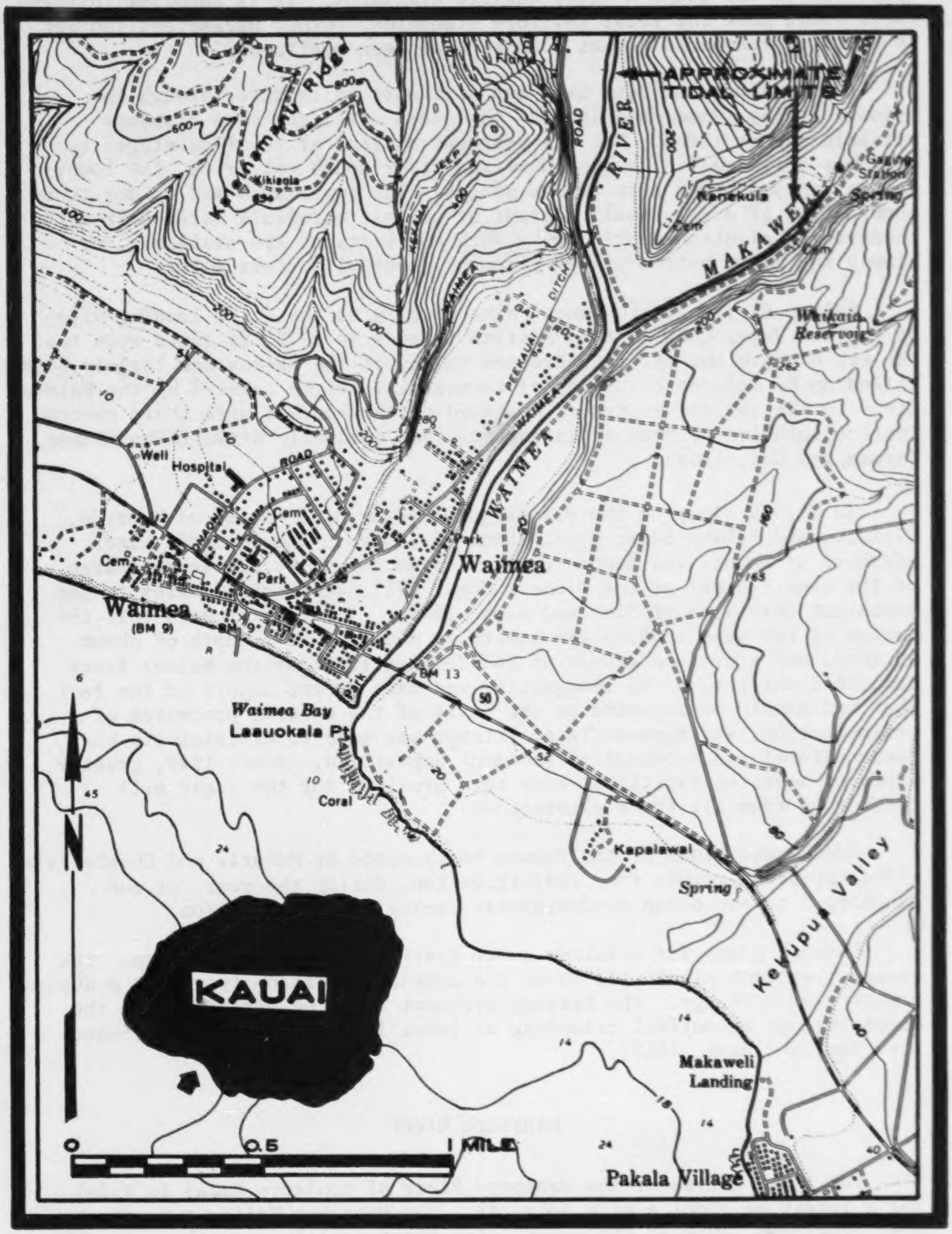


FIGURE 3. WAIMEA RIVER.

which exceed the Class A water quality standards. It is doubtful that the water would meet the fecal coliform standards. Other parameters subject to specific standards do not seem to have been monitored.

Large amounts of both sand and silt must be carried through the estuary during flood when, indeed, the ocean water for some distance offshore may be turbid, but the sediment content at low-flow stages is probably very small. As most Hawaiian river mouth estuaries, the lower Waimea appears brown even at low stages. The appearance may be due to a combination of a very small content of organic materials derived from the headwaters, plankton nourished by such nutrients as are available, or simply the muddy bottom viewed through essentially clear water.

Waimea Bay, which is famous historically as the first landing site of Captain James Cook in the Hawaiian Islands in 1778, is quite open to the sea because the original drowned valley of the Waimea has largely been filled up by sediments. Sands of terrestrial origin carried by the Waimea River to the sea may be traced westward on the beaches with their concentration, relative to that of calcareous sand, gradually diminishing (Inman, Gayman, and Cox, 1963).

In a 1949 study of the discharge of sugar mill wastes of McBryde, Olokele, and Kekaha Sugar plantations of southern Kauai, muddy water offshore at Waimea was found to result from the drift of the discharge of the cane cleaner at the Olokele Sugar Mill, about three miles to the southeast (Division of Fish and Game, 1949). The report noted that the bottom of the area studied was generally mud-free to a depth of about 40 feet, but a dredged sample at 180 feet in front of the Waimea River indicated thick mud. No recognition was made in the report of the fact that mud should be expected on the basis of the natural processes of sedimentation, and apparently no attempt was made to discriminate between natural and accelerated sediment deposition. Since 1949, greatly improved settling facilities have been provided for the sugar mill discharges from all three plantations.

Muddy conditions of the Waimea beach noted by Moberly and Chamberlain (1964) probably result from redistribution, during the year, of mud discharged to the ocean predominantly during the flood season.

General plans for a Waimea sewer district have been drawn up. The sewage treatment plant will be of the extended aeration type with a design capacity of 0.28 mgs. The treated effluent is to be discharged to the ocean through an outfall extending at least 1,000 feet offshore (Sunn, Low, Tom, and Hara, 1963).

Hanapepe River

The lower course of the Hanapepe River of southern Kauai is tidal for a length of about a mile (Fig. 4). The Hanapepe Valley cuts through post-erosional lavas at the coast. Its coastal plain near the coast is between 2,000 and 3,000 feet in width. There is an area of salt marshes on the east bank of the river near its mouth. In dry weather the mouth

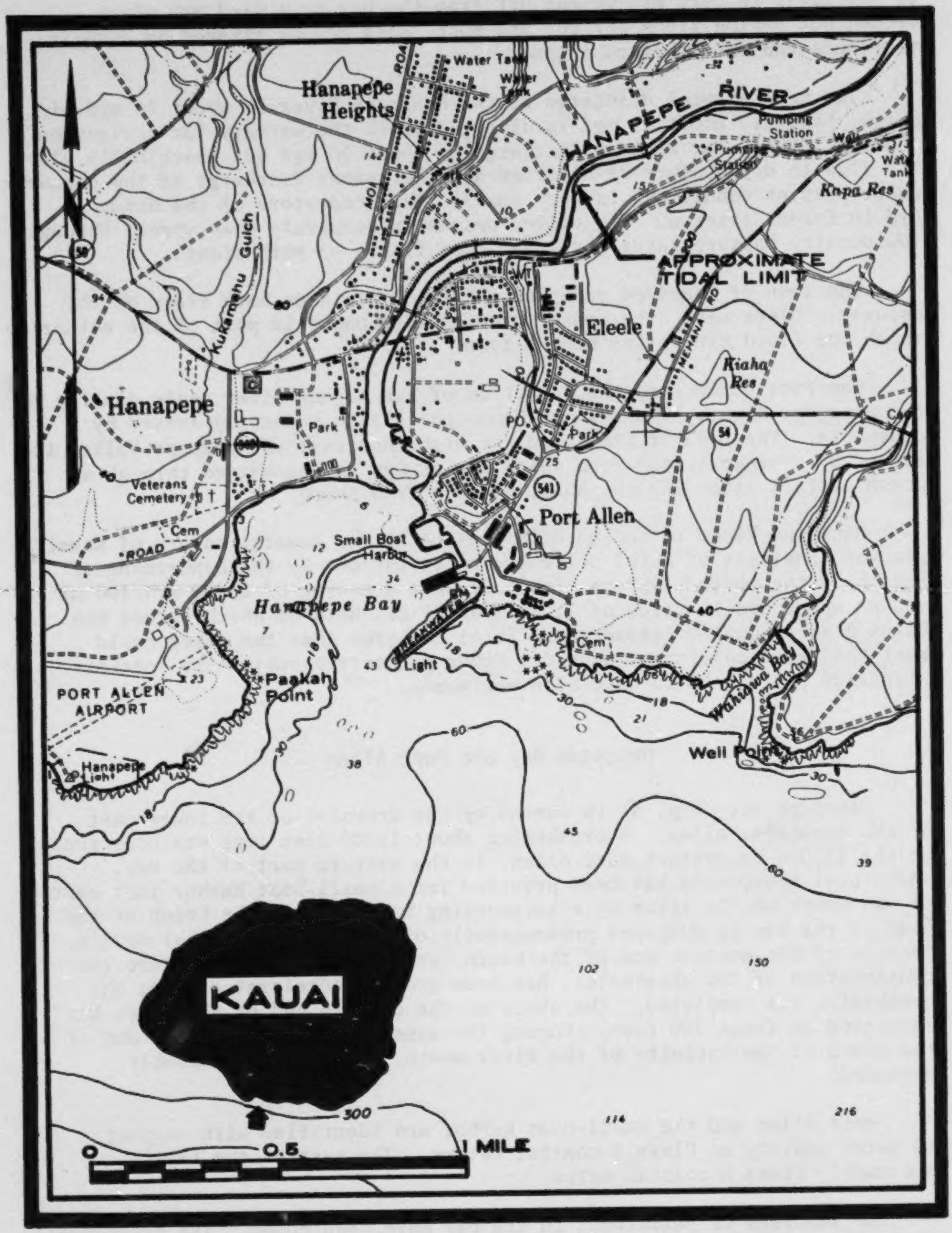


FIGURE 4. HANAPEPE RIVER AND BAY, PORT ALLEN, AND WAHIAWA BAY.

of the river is very nearly cut off from the bay by a sand bar which is eroded out during flood periods and must sometimes be removed by dredging to reduce the flood hazard inland.

The mean natural discharge of the Hanapepe River is about 80 mgd of which, however, about 45 mgd is diverted above the estuary for irrigation (Davis, 1960). The minimum discharge is about 30 mgd but practically all the flow in dry weather is diverted and the summer discharge of the estuary under present conditions is very small. The headwaters of the Hanapepe are in forest reserve. The valley passes successively down stream through low-density pasture lands and sugar cane fields on both sides.

The town of Hanapepe occupies the flood plain on both sides of the estuary. Dikes have been constructed on both banks in part of the estuarine reach for flood protection of the town.

Comments concerning the pollution of the Waimea River apply equally to the Hanapepe River. The town of Hanapepe is also presently served by cesspools. The town of Eleele on the highlands east of Hanapepe Valley is served by a sewer system from which raw sewage is discharged through an ocean outfall extending out about 50 feet from shore.

Hanapepe River is included in Class A of the coastal waters of Kauai. However, analyses of total coliform concentrations by the Department of Health in the period 1959-63 (Table 5) have a median of 2,400 MPN/100 ml and an upper decile value of 7,000 MPN/100 ml, both of which exceed the Class A water quality standards. It is doubtful that the water could meet the fecal coliform standard. Other parameters subject to specific standards appear not to have been monitored.

Hanapepe Bay and Port Allen

Hanapepe Bay (Fig. 4) is formed by the drowning of the lower part of the Hanapepe Valley. A breakwater about 1,000 feet long was constructed in the 1930's to protect Port Allen, in the eastern part of the Bay. Additional protection has been provided for a small-boat harbor just east of the mouth of the river by a surrounding breakwater. The beach at the head of the bay is composed predominantly of sand of terrestrial origin. Erosion of the western end of the beach, which perhaps began before the construction of the breakwater, has been greatly accelerated since the breakwater was completed. The shore at the eastern end of the beach has retreated at least 200 feet. During the same period, the western end of the beach in the vicinity of the river mouth, has been considerably extended.

Port Allen and the small-boat harbor are identified with respect to water quality as Class B coastal waters. The rest of the Bay is presumably Class A coastal water.

No analyses of pollutants in the bay have been found. The predictable kinds of pollution associated with the activities of the commercial port probably result in low concentrations of pollutants because of the good flushing characteristics of the bay. Floods of the Hanapepe River are, of course, accompanied by turbid conditions in the bay. Generally the Bay clears up relatively rapidly, although Moberly and Chamberlain (1964) noted that muddy conditions detracted from the attractiveness of the beach for swimming.

Plans for a Hanapepe sewer district, which will include the towns of Hanapepe, Eleele, and Port Allen, call for a primary sewage treatment plant, to be located in the port area, from which the chlorinated effluent will be discharged through an outfall extending 200 feet offshore east of the Port Allen breakwater, in an area where there are good mixing conditions and a predominantly westward setting current of about one knot (Laevastu, Avery, and Cox, 1964).

Wahiawa Bay

Wahiawa Bay (Fig. 4), a mile east of Hanapepe Bay, is the drowned mouth of the valley of Wahiawa Stream eroded into post-erosional lavas. All of the dry weather flow of Wahiawa Stream is diverted inland for irrigation, and even flood discharges are materially reduced by the large Alexander reservoir in the mountain area.

A failure of the Alexander Dam during its construction period in the 1930's resulted in the transport of large volumes of mud downstream to the Bay. At the head of the Bay is a beach, composed originally of sand of predominantly calcareous composition, which was extensively used for recreation prior to the 1930's. Since the dam failure, the waters of the Bay have been muddy and the composition of the beach sand is now predominantly terrestrial. The former estuary at Wahiawa Stream, which was formerly navigable by skiff for about a quarter mile, is now filled with mud.

The Division of Fish and Game (1949) mapped Wahiawa Bay as within the plume of muddy water discharged from the cane washer of the McBryde mill, about a mile east of the Bay. The Division reported a greatly reduced oxygen concentration in the water at the ocean surface at the edge of the plume. The study reported mud on the bottom from 95 to 150 feet deep off Wahiawa, but did not consider whether its source was natural sedimentation, sedimentation resulting from the Alexander dam failure, or sedimentation of the cane washer discharge from McBryde mill.

Since 1949 improved settling facilities have considerably reduced the ocean discharge of mud and organic wastes from the cane washer. However, a Federal Water Pollution Control Administration study (in preparation) has shown that Wahiawa Bay was within the plume of the McBryde mill discharge in April 1968, and that secchi disk visibility in the Bay was only 8 to 12 feet.

By reason of its location, Wahiawa Bay is included in coastal water Class A. However, the turbidity indicated above would exceed the standards for this class, unless the natural background from which the turbidity change is to be computed is the flood-stage background or unless Wahiawa Bay is included in a "Zone of Mixing" established for the McBryde discharge.

Lawai Stream and Bay

Lawai Bay (Fig. 5), which has approximately the same dimensions as Wahiawa Bay about 4-3/4 miles to the west, is the drowned mouth of the valley of Lawai Stream cut by the stream through post-erosional lavas. At the head of the Bay is a calcareous sand beach much like that originally found at Wahiawa. The stream mouth is navigable by skiff inland for about half a mile. Practically the entire low flow of the stream is diverted inland for irrigation and a series of small reservoirs probably reduces flood flows as well. At times the sand bar at the mouth of the stream completely isolates the stream from the bay.

By reason of its location, Lawai Stream and Lawai Bay is included in coastal water Class A. No analyses of the water appear to be available to determine whether or not their water quality falls within the standards for this class.

Nawiliwili Bay

Nawiliwili Bay (Fig. 6) is a well-developed bay estuary in the southeast coast of Kauai which serves as the principal harbor for the island.

The Bay lies between a rugged ridge composed of the original flank flows of the Kauai volcano to the south and gently sloping post-erosional lavas to the north. It represents the drowned valley that was formed by the confluence, at a lower stand of the sea, of the Huleia Stream and Puali and Nawiliwili Streams. The principal supply of fresh water is from the Huleia Stream, the lower part of which is a stream-mouth estuary. The other streams have inconsequential estuarine lower reaches.

Large areas in the drainage basins of all three streams are in sugar cane fields of comparatively low relief and there is a large cattle ranch in the drainage basin of the Huleia Stream. The headwaters of the Nawiliwili and Puali Streams are in the flat-sloped post-erosional lava dome of Kilohana. The headwaters of the Huleia are in the extremely rugged Waialeale-Kawaikini mass of central Kauai. Irrigation water is diverted from all three streams.

Nawiliwili Bay was early used as a harbor, but the present harbor development dates from the 1930's when an outer breakwater and inner seawall were constructed and the harbor was deepened by dredging. Additional dredging was done about 1958 to produce coral for use in road construction, and a large stockpile of coral rubble was left in the form of a promontory between the main harbor basin and the Puali Stream mouth. Bulk-sugar handling facilities were installed about 1957. Sugar, molasses, and pineapple are the principal exports through the harbor and general merchandise, building materials, and oil the principal imports.

Since the coral-storage promontory was constructed about 1958, the head of the bay has silted up rapidly. The former calcareous sand beach at the County Park at Niumalu is now partly buried and cut off from the

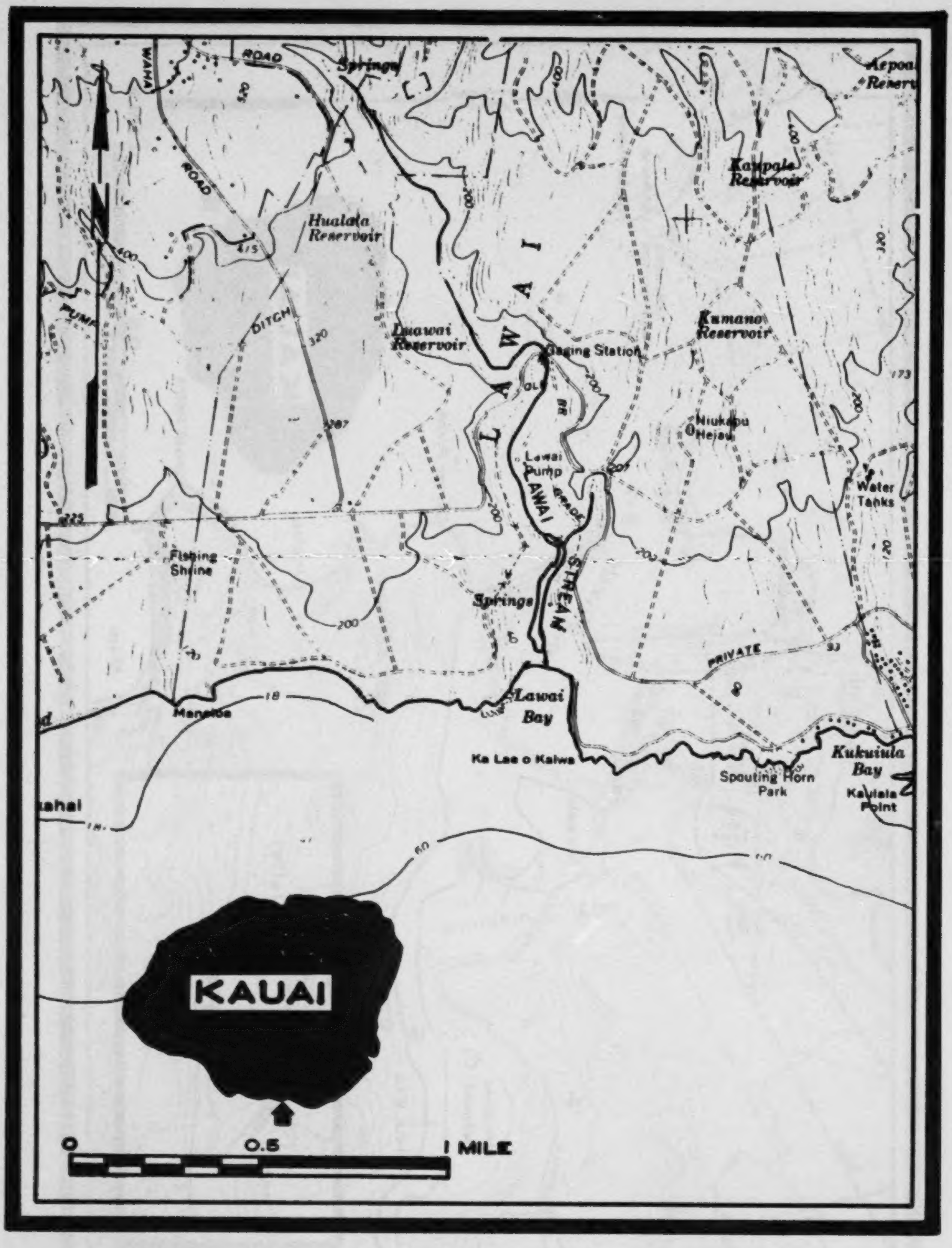


FIGURE 5. LAWAI STREAM AND BAY.

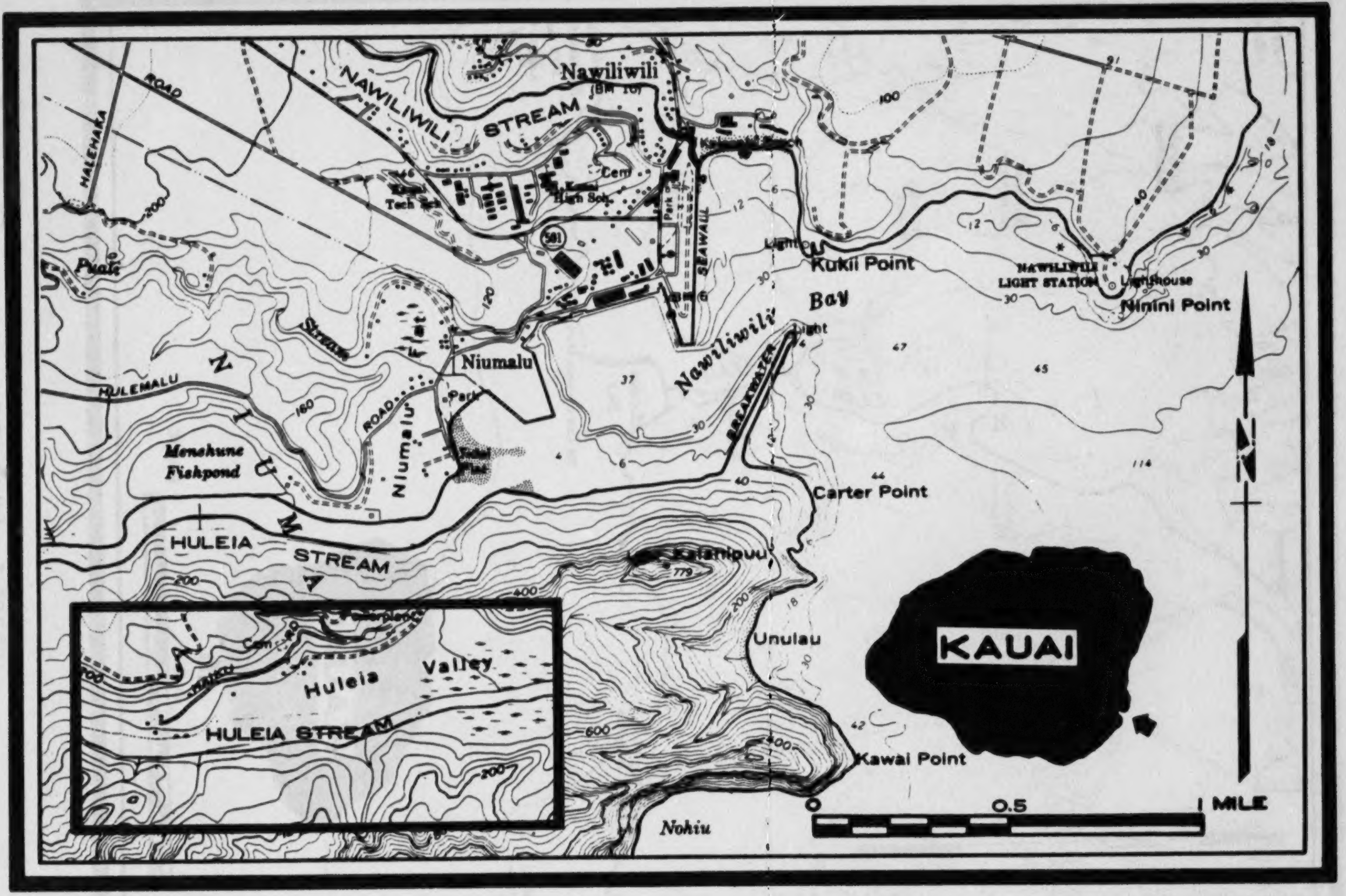


FIGURE 6. NAWILIWILI BAY AND HULEIA STREAM.

bay by a mangrove swamp, which is now much wider than the tide flats shown on the map (Fig. 6), which is based on 1960 air photographs. A sand bar, which formerly built between floods, restricting the entrance from the Huleia Stream into the Bay, apparently does not rebuild under the present reduced wave conditions at the head of the Bay.

Kalapaki Beach, located at the head of the northern arm of the Bay, outside the harbor sea wall, is a calcareous sand beach. The bay bottom in front of the beach is sand and the swimming is good (Moberly and Chamberlain, 1964).

According to Moberly and Chamberlain (1964), there is a counter-clockwise current in Kalapaki Bay but it is never strong unless the sea is very rough. Currents in the harbor itself are probably weak. The few nearshore-current measurements outside the Bay (Laevastu, Avery, and Cox, 1964) show a complex reversing current probably related to the tide.

The town of Lihue is located partly in the valley of Nawiliwili Stream, and the sugar mill of Lihue Plantation Company lies in the valley about 1-1/2 miles from the harbor. Some millyard drainage as well as urban storm drainage undoubtedly reach the bay by way of this stream, but the cane-cleaner wash water is diverted for use in irrigating fields farther north and wastes to the sea about a mile north of Ninini Point, the northern point of Nawiliwili Bay. The town is at present served by cesspools.

The village of Nawiliwili, located on the floor of Nawiliwili Valley and on the ridge to the south, and the village of Niumalu, located on the floor of Huleia Valley at the head of the Bay, are at present served by cesspools.

The Kauai Surf, a major hotel complex, was constructed at Kalapaki Beach about 1962. The hotel complex has an extended-aeration sewage treatment plant from which the chlorinated effluent is diluted with fresh water and discharged, after passage through a lagoon, to the Bay along the front of Kalapaki Beach (Sunn, Low, Tom, and Hara, 1963).

A sewage treatment plant to serve the Lihue sewer district, including Lihue, Nawiliwili, and Niumalu, has been built, but the sewer lines and outfall have not yet been completed. According to original plans for the outfall, it would have discharged into Nawiliwili Bay, inside the outer breakwater. However the revised plans call for the sewage to be discharged into a ditch which runs behind Kauai Surf and empties into the ocean near Ahukini Point, which is north of the Bay.

A substantial silt load, chemical and livestock wastes, cesspool seepage, and thermal waters were listed as possible pollutants of Nawiliwili Bay in the hearings on Water Pollution Control standards (Department of Health, 1967a). The silt load of the streams is not monitored. It seems unlikely that this load greatly exceeds natural levels or that livestock wastes are significant. No actual evidence of the existence of cesspool seepage or other bacterial contamination has yet been located. The only source of high-temperature water would appear to be Lihue mill. However, its high-temperature waste waters may not flow to the Bay at all, and in any case would seem likely to be effectively cooled in the surface flow between the mill and Bay. Stray cane trash may arrive at the Bay either by way of Nawiliwili Stream or by long-shore drift from the outfall north of the Bay. The commercial harbor activities undoubtedly contribute some pollution, but levels of most pollutants are not known.

With respect to water quality, Nawiliwili Bay has been designated as a Class B coastal water. The extent to which this designation is intended to cover the entire Bay or be restricted to the harbor is uncertain in the light of the swimming use that forms a basis for Class A classification and the restriction in the definition of Class B waters that they "shall apply only to a limited area next to boat docking facilities in bays and harbors. The rest of the water area in such a bay or harbor shall be Class A unless given some other specific designation..." (Department of Health, 1968). In the light of this restriction the Kalapaki arm of the Bay, if not the outer Bay as a whole, must be considered to be included in Class A.

Department of Health analyses of total coliform concentrations (Table 5) in the period 1959-63 have a median of only 230 MPN/100 ml and an upper decile value of 2,400 MPN/100 ml, both within the standards for Class A waters. The coliform concentration for the period 1959-69 at the one station at Kalapaki Beach with a long record has a somewhat higher median of 620 MPN/100 ml and an upper decile value of 7,000 MPN/100 ml. The latter value exceeds the standard for Class A water.

A detailed study of the biological, chemical, and physical characteristics of Nawiliwili Harbor planned by the Federal Water Pollution Control Administration should enormously increase the amount of factual information pertaining to the pollution of the estuary.

Huleia Stream

The lower reach of the Huleia Stream (Fig. 6) is tidal for a distance of about 1.5 miles from its entrance into Nawiliwili Bay. At its mouth, the Huleia valley lies between a ridge composed of the original flank lavas of the Kauai volcano to the south and a plateau to the north underlain by post-erosional lavas. Farther inland both walls of the valley are composed of post-erosional lavas.

The dry-weather flows of the Huleia Stream are diverted far inland for irrigation. There are no recent gage records for the lower reaches of the Stream, but from 1912 to 1915 the stream was gaged at 200 feet altitude (Territorial Planning Board, 1939). At this time the headwater diversions were already in existence and the records indicate present discharge through the estuarine lower reach reasonably well. The mean flow indicated was about 14 mgd, the median about 6.5 mgd, and the minimum nearly 3 mgd. The duration-discharge relation is shown in Figure 7.

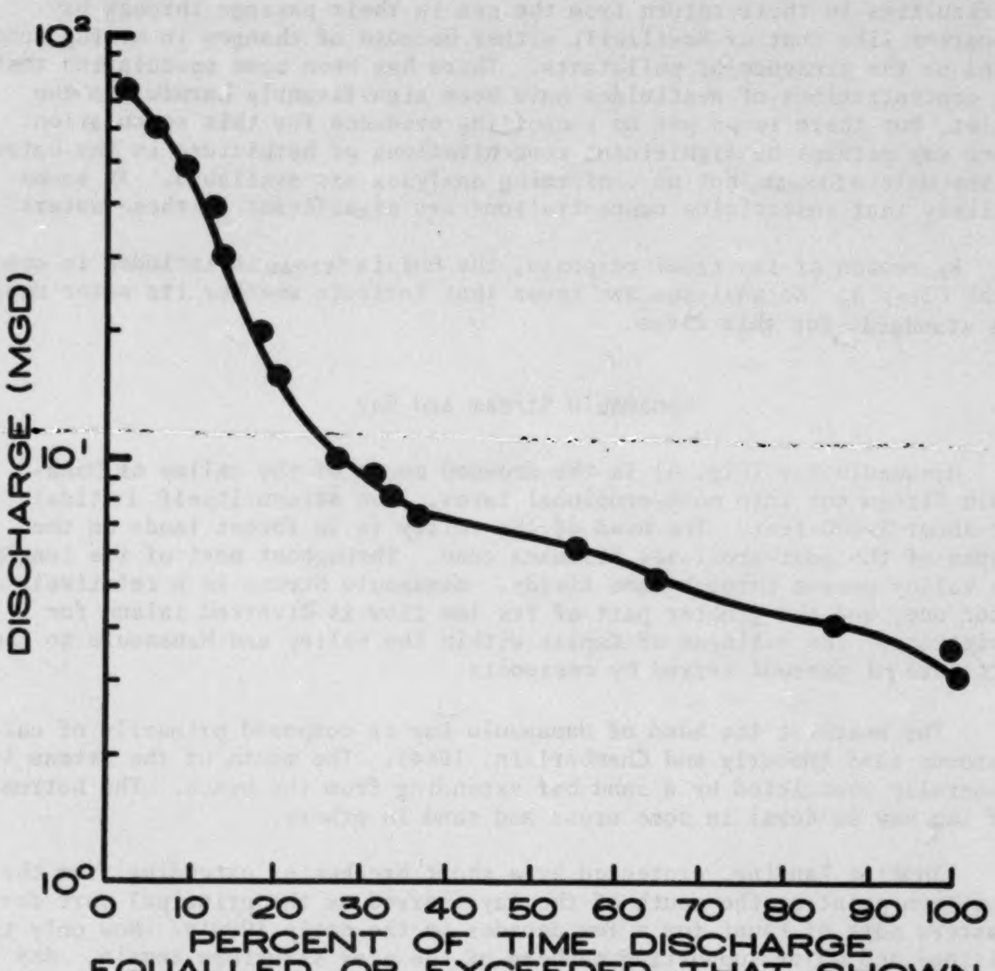


FIGURE 7. DURATION DISCHARGE CURVE OF HULEIA RIVER (USGS NO. 62).

A large fishpond on the north bank of the Huleia estuary, now in poor condition, is of archeological importance, having been constructed by the Menehune according to legend. The abandonment of the Menehune Fish Pond, the causes of which are not well established, is undoubtedly related to the general decline of the mullet industry in the Islands. Silting of the old fish ponds is common on many coasts, but the relative importance of accelerated rates of sedimentation and decreased attention to silt removal is unknown. It is difficult to see why silting in the Menehune Fish Pond should have been so greatly accelerated. The young mullet may face increasing difficulties in their return from the sea in their passage through bay estuaries like that of Nawiliwili either because of changes in mixing conditions or the presence of pollutants. There has been some speculation that low concentrations of pesticides have been significantly harmful to the mullet, but there is as yet no supporting evidence for this speculation. There may perhaps be significant concentrations of herbicides in the waters of the Huleia Stream, but no confirming analyses are available. It seems unlikely that insecticide concentrations are significant in these waters.

By reason of its tidal response, the Huleia Stream is included in coastal water Class A. No analyses are known that indicate whether its water meet the standards for this class.

Hanamaulu Stream and Bay

Hanamaulu Bay (Fig. 8) is the drowned mouth of the valley of Hanamaulu Stream cut into post-erosional lavas. The stream itself is tidal for about 1,000 feet. The head of the valley is in forest lands on the slopes of the post-erosional Kilohana cone. Throughout most of its length, the valley passes through cane fields. Hanamaulu Stream is a relatively minor one, and the greater part of its low flow is diverted inland for irrigation. The villages of Kapaia within the valley and Hanamaulu to the north are at present served by cesspools.

The beach at the head of Hanamaulu Bay is composed primarily of calcareous sand (Moberly and Chamberlain, 1964). The mouth of the stream is generally restricted by a sand bar extending from the beach. The bottom of the bay is coral in some areas and sand in others.

Ahukini Landing, protected by a short breakwater extending from the southern point at the mouth of the Bay, served as the principal port for the eastern part of Kauai for a few decades in the early 1900's. Now only the pilings and major supporting members of the pier structure remain. Any contamination that resulted from the use of the Bay as a commercial landing has now disappeared. There is a county park on the beach at the head of Hanamaulu Bay but it is not heavily used, the waters of the Bay being considered not especially good for swimming, reportedly because of the discharge of muddy water from the stream (Moberly and Chamberlain, 1964).

By reason of location and tidal behavior, both Hanamaulu Stream and Hanamaulu Bay are included in coastal water Class A. However, the Department of Health analyses of total coliforms in the Bay at the County Park Beach, in the period 1959-69 (Table 5) have a median of 620 MPN/100 ml

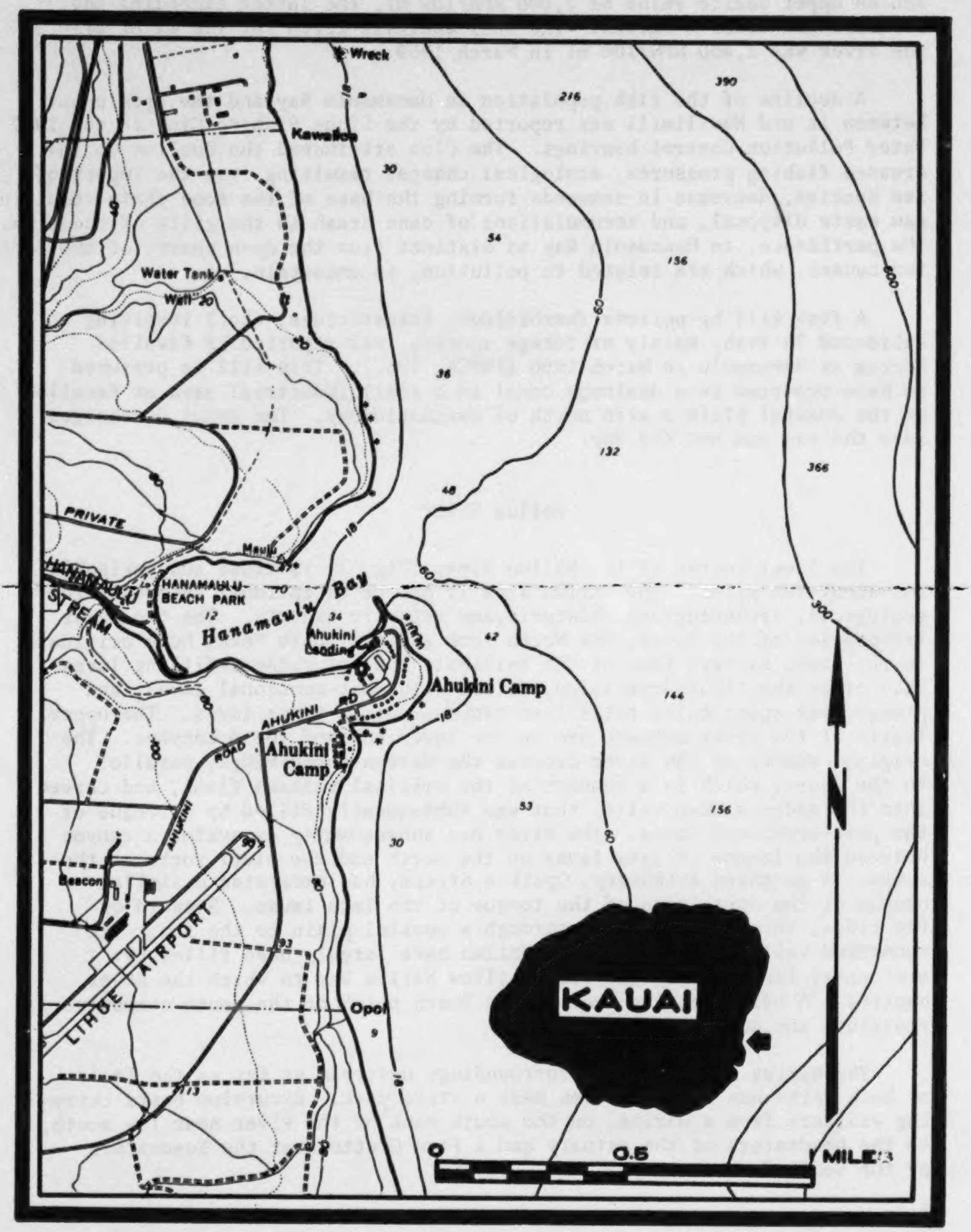


FIGURE 8. HANAMAULU STREAM AND BAY.

and an upper decile value of 7,000 MPN/100 ml, the latter exceeding the standard for Class A waters. The only analysis given for the water of the river was 2,400 MPN/100 ml in March 1959.

A decline of the fish population in Hanamaulu Bay and the open coast between it and Nawiliwili was reported by the Lihue Fishing Club to the 1967 Water Pollution Control hearings. The Club attributed the decline to increased fishing pressures, ecological changes resulting from the import of new species, decrease in seaweeds forming the base of the food chain resulting raw waste disposal, and accumulations of cane trash in the gills of the fish. The pertinence, to Hanamaulu Bay as distinct from the open coast, of the latter two causes, which are related to pollution, is uncertain.

A fish kill by poisons (herbicides, insecticides, etc.) involving an estimated 70 fish, mainly of forage species, was reported in Kawailoa Stream at Hanamaulu in March 1966 (FWPCA, 1967). This kill is presumed to have occurred in a drainage canal in a small industrial area at Kawailoa on the coastal plain a mile north of Hanamaulu Bay. The canal discharges into the sea and not the Bay.

Wailua River

The lower course of the Wailua River (Fig. 9) is tidal and navigable for about two miles. The Wailua area is one of exceptional interest from geological, archeological, historic, and esthetic aspects. The two major tributaries of the River, the North Fork and the South Fork, both originate on the steep eastern face of the Waialeale mass of caldera-filling lavas. They cross the Lihue depression, filled with post-erosional lavas, and plunge over spectacular falls into canyons cut in these lavas. The upper limits of the river estuary are in the lower ends of these canyons. The original valley of the River crossed the Kalepa-Nonou ridge, parallel to the shore, which is a remnant of the original volcano flank, and carved into the ridge a deep valley that was subsequently filled by a tongue of the post-erosional lavas. The River has subsequently excavated a canyon between the tongue of late lavas on the north and the older rocks on the south. A northern tributary, Opaikaa Stream, has excavated a similar canyon at the north edge of the tongue of the late lavas. Seaward of the ridge, the estuary passes through a coastal plain to the sea. The submerged valleys of Opaikaa and Wailua have largely been filled by sediments, leaving only the very shallow Wailua Bay to which the River empties. A bar extending from Wailua Beach north of the mouth commonly restricts the mouth of the River.

The Wailua River and its surroundings upstream as far as the falls on both forks has recently been made a state park. Excursion boats carrying visitors from a marina, on the south bank of the River near its mouth, to the headwaters of the estuary and a Fern Grotto near the headwaters of the south fork estuary.

The mean natural discharge of the North Fork of the Wailua is about 72 mgd and that of the South Fork about 118 mgd making a total natural

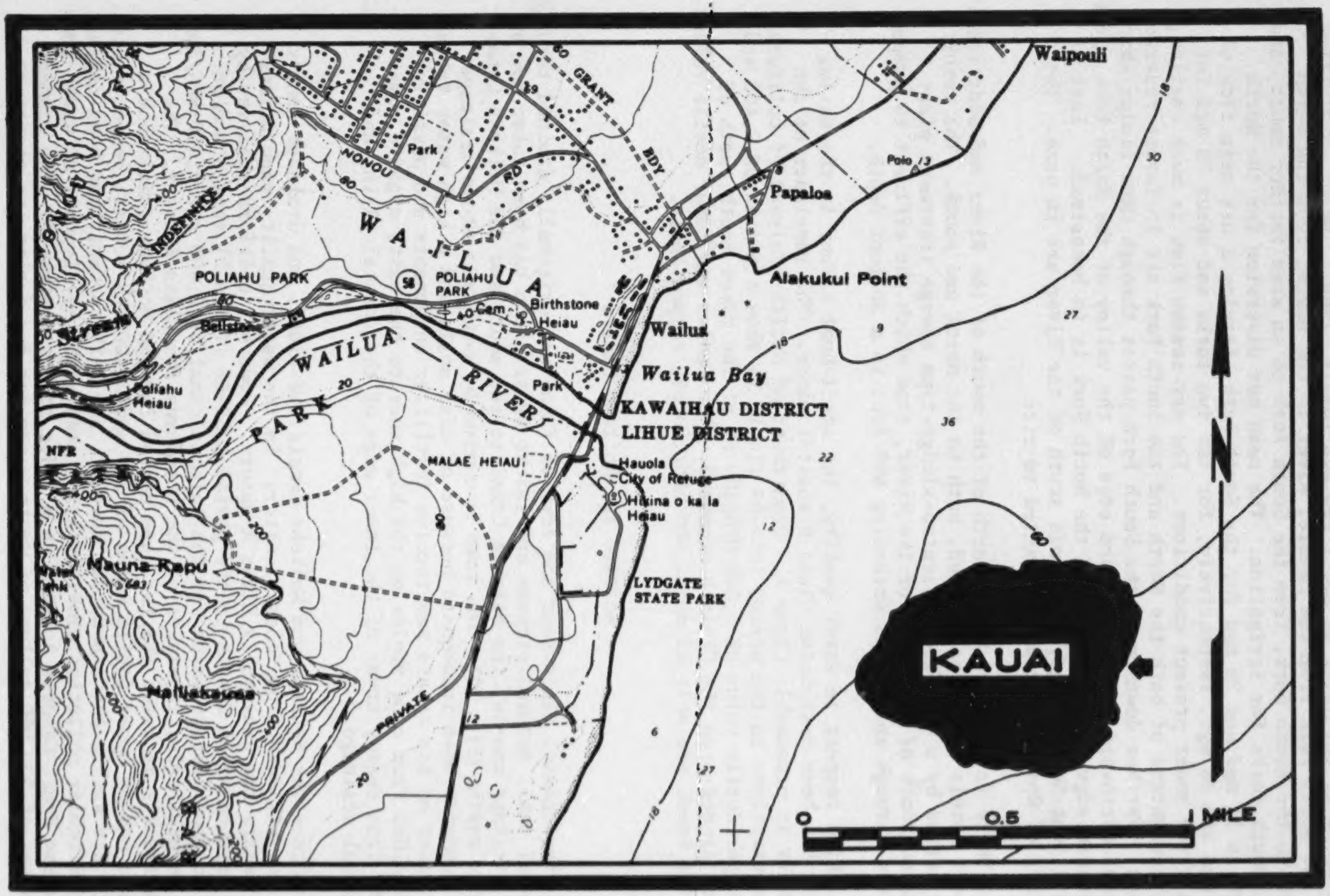


FIGURE 9. WAILUA RIVER.

discharge of the River of about 190 mgd (Davis, 1960). Water is diverted to the North Fork from the Hanalei River to the north, from the North Fork to the South Fork, from the South Fork to an area farther south, and from both forks for irrigation. The mean net diversion for the North Fork is 31 mgd and 70 mgd for the South Fork, leaving a net mean flow of 41 mgd and 38 mgd, respectively, for the two forks and about 79 mgd for the River under present conditions. The dry-season flow is much smaller. The headwaters of both the North and the South Fork are in forest reserve lands. Farther downstream the South Fork passes through cane fields which extend northward to the southern edge of the valley of the North Fork. The northern edge of the valley of the North Fork is in homesteads. East of the Kalepa-Nonou Ridge, the lands south of the River are in cane. The valley of Opaikaa Stream is planted to rice.

There is a resort hotel north of the mouth of the River and additional resort hotels are being erected, both to the north and south. The resorts are served by a modified activated-sludge-type sewage treatment plant located south of the mouth of the River, from which the effluent is pumped to sea through an outfall extending 600 feet to a 30-foot depth.

With respect to water quality, the small-boat harbor in the Wailua River has been designated Class B coastal water. The remainder of the estuary is presumably Class A. Department of Health analyses of coliform concentrations in the period 1959-69 (Table 5) show a median of 2,400 and an upper decile value of 7,000 MPN/100 ml at the river mouth, both of which exceed even the Class B standard. The median and upper decile values on the beach are only 62 and 2,400 MPN/100 ml, respectively.

Waiakea and Moikeha Canals

The coastal plain near the town of Kapaa was originally drained through several small natural streams and inlets whose place has been taken now by two drainage canals, the Waiakea Canal to the south and the Moikeha Canal to the north (Fig. 10). The town is served by cesspools whose drainage has commonly been inadequate because of clay soils and a high water table. The water of the canals may receive fertilizer components and possibly herbicides from cane fields on the highlands to the east, organic components from swampy areas of the inner edge of the coastal plain, and cesspool drainage.

Since the Waiakea and Moikeha Canals are tidal, and drainage canals are not excluded from "coastal waters" in the water quality regulations. The canals are presumably Class A waters. However, coliform analyses by the Department of Health in the period 1959-63 (Table 5) show a median and an upper decile value for the Waiakea canal of 2,400 and 7,000 MPN/100 ml, respectively, in excess of the standards for Class A water. The Department's analyses for the same period for the Moikeha Canal show a median and an upper decile value of 230 and 2,400 MPN/100 ml, respectively, which are within the standard. However, the Moikeha Canal has been subject to particular pollution problems associated with the disposal of waste from Hawaiian Fruit Cannery located on a ridge to the northwest. The cannery disposes of 300,000 gallons of waste water per day during its operating

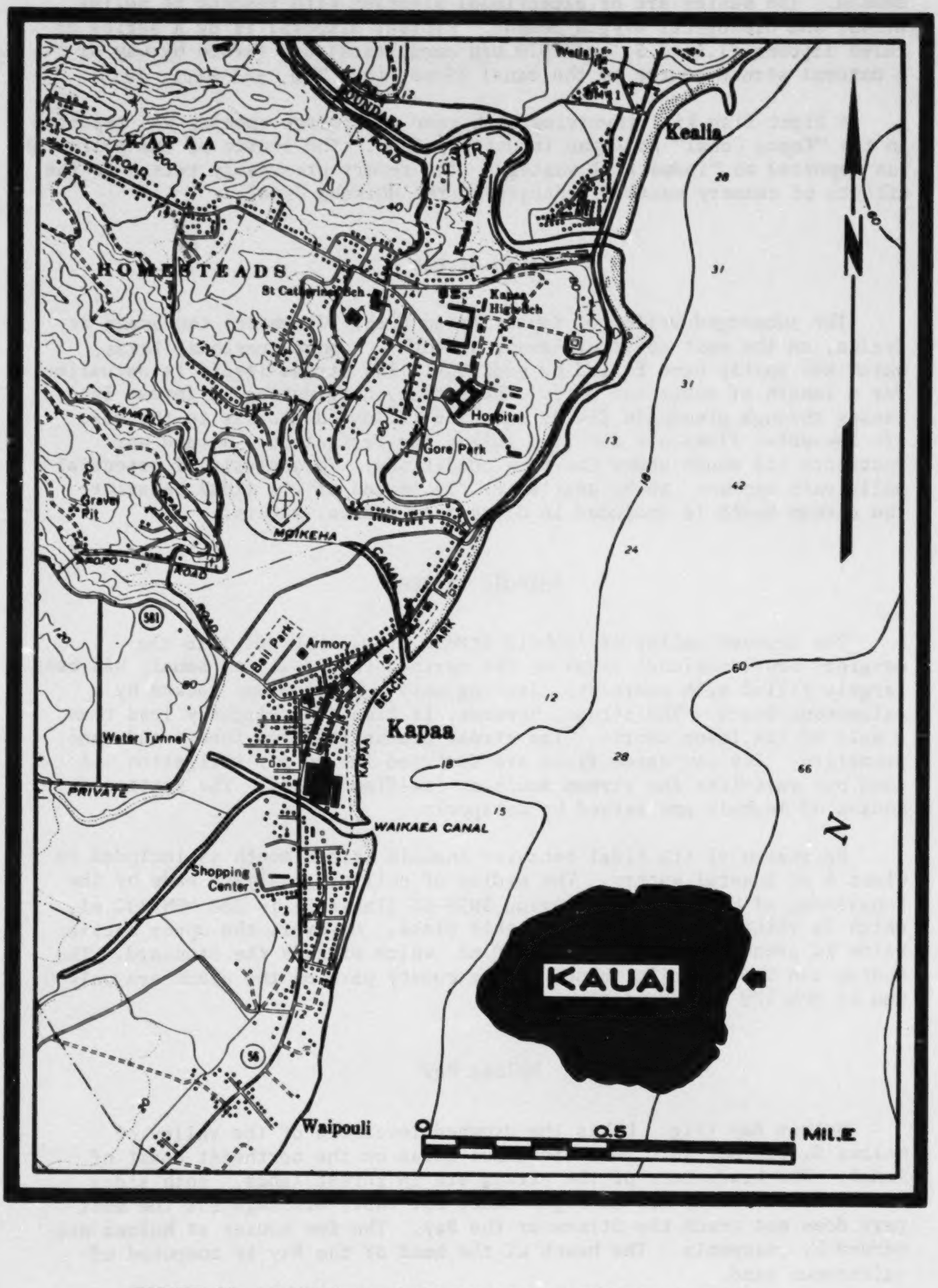


FIGURE 10. WAIAKEA AND MOIKEHA CANALS AND KAPAA STREAM.

season. The wastes are of exceptional strength with respect to solids, acids, and biological oxygen demand. Present disposal is by a series of three lagoons (1.5, 7.5, and 15.0 mgd capacities) and thence by way of a natural stream course to the canal (Sunn, Low, Tom, and Hara, 1963).

A light fish kill involving both game and forage species was reported in the "Kapaa Canal" at Kapaa in October 1960. The source of the pollution was reported as "industrial wastes." The report presumably refers to the effects of cannery waste discharged to the Moikeha Canal.

Kapaa Stream

The submerged valley of Kapaa Stream (Fig. 10) enters the ocean at Kealia, on the east coast of Kauai, through post-erosional lavas, which has mostly been filled by sediment. The stream itself is estuarine for a length of about one mile. The stream, originating in forest lands, passes through pineapple fields and cane fields on its way to the sea. Its low-water flows are diverted inland for irrigation. A sand bar restricts its mouth under low-flow conditions. No analysis of potential pollutants appears to be available. By reason of its tidal behavior the stream mouth is included in Class A of coastal waters.

Anahola Stream

The drowned valley of Anahola Stream (Fig. 11) cut into the marginal post-erosional lavas on the northeastern coast of Kauai, has been largely filled with sediments, leaving only a shallow bay backed by a calcareous beach. The stream, however, is tidal for slightly less than a mile of its lower course. The stream drains lands in forest and cane, primarily. Its low-water flows are diverted inland for irrigation. A sand bar restricts the stream mouth at low-flow stages. The scattered houses of Anahola are served by cesspools.

By reason of its tidal behavior Anahola Stream mouth is included in Class A of coastal waters. The median of coliform analyses made by the Department of Health in the period 1959-63 (Table 5) is 230 MPN/100 ml, which is within the standard for this class. However, the upper decile value is greater than 7,000 MPN/100 ml, which exceeds the standard. The median and upper decile values at the county park on the beach are only 0 and 62 MPN/100 ml, respectively.

Moloaa Bay

Moloaa Bay (Fig. 12) is the drowned lower end of the valley of Moloaa Stream cut into post-erosional lavas on the northeast coast of Kauai. The headwaters of the stream are in forest lands. Both sides of the lower valley are in sugar cane, but their drainage for the most part does not reach the Stream or the Bay. The few houses at Moloaa are served by cesspools. The beach at the head of the Bay is composed of calcareous sand.

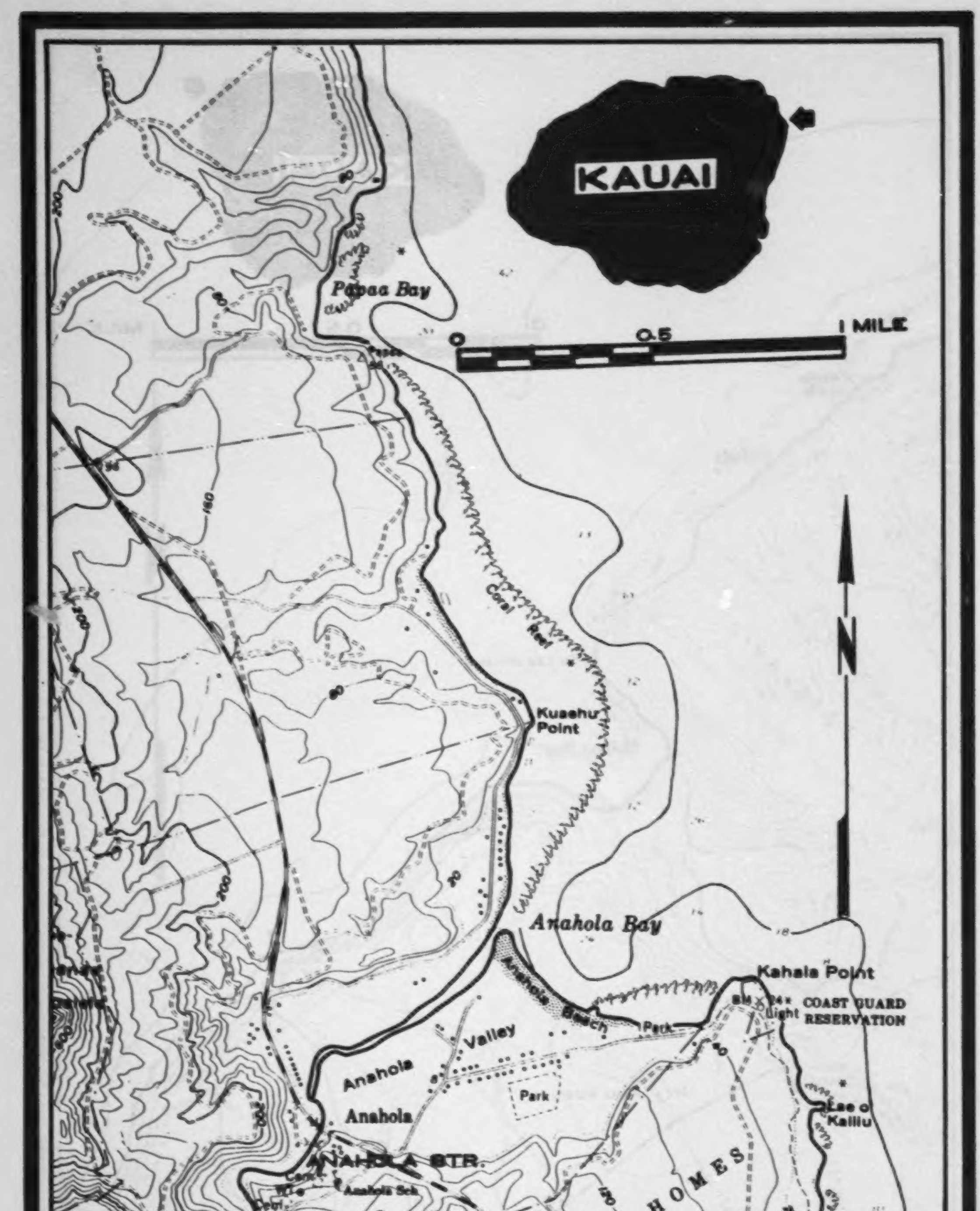


FIGURE 11. ANAHOLA STREAM.

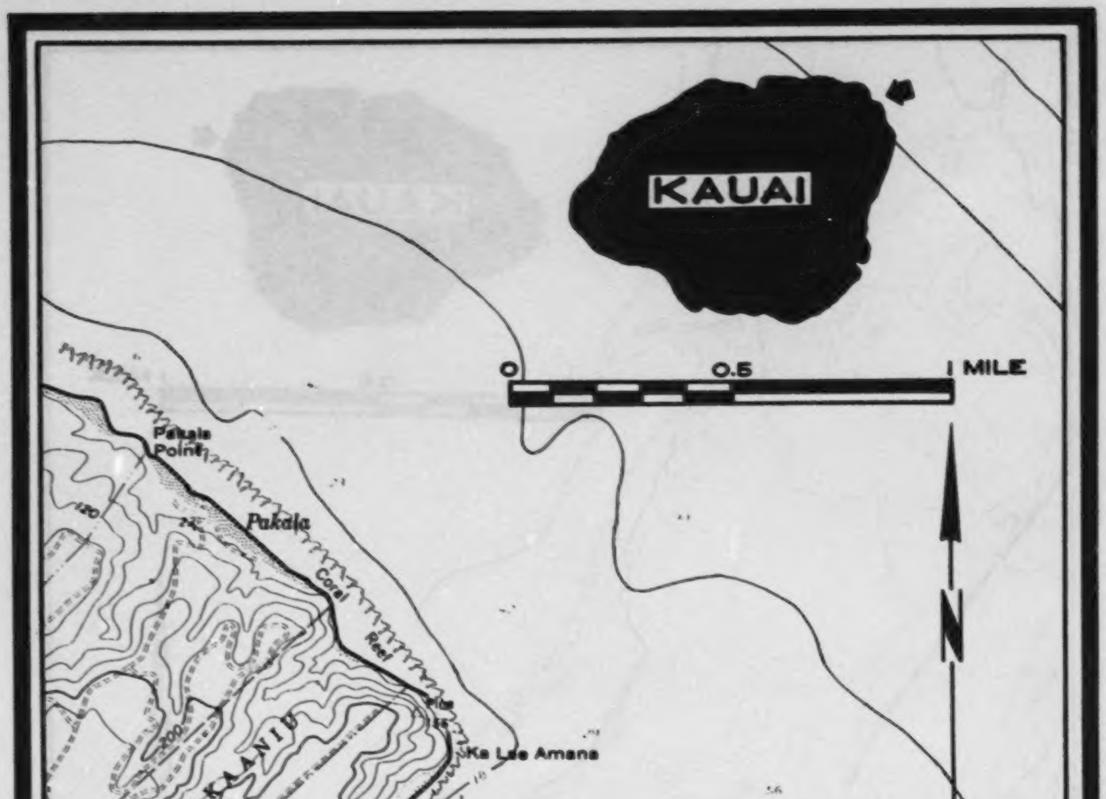


FIGURE 12. MOLOAA BAY.

Moloaa Bay is included in Class A of coastal waters. It seems very unlikely that there is any significant pollution of the Bay from immediate land sources, except freshet-born mud. However, in the summer of 1968, the water was turbid as the result of apparently organic suspended material. The source of this material is unknown. It may perhaps represent cane wastes drifting from the Kilauea mill disposal site (see section on Kalihiwai), but no other evidence suggests a drift so far to the east.

Kilauea Stream and Bay

Kilauea Bay, on northern Kauai (Fig. 13), is the drowned seaward portion of the valley cut by Kilauea Stream in post-erosional lavas. The Stream itself is tidal for a length of about a mile. It originates in forest lands and flows through cane fields on its way to the estuary. Its low-water flows are diverted inland for irrigation. A sandbar restricts the stream mouth at low-flow stages. A tuff quarry on the western bank at the mouth of the Stream does not appear to be a source of significant pollution to either the Stream or the Bay. For the town of Kilauea, now served by cesspools, an oxidation pond has been proposed from which chlorinated effluent will be discharged through a ditch presumably to the Stream and Bay (Sunn, Low, Tom, and Hara, 1963).

By reason of their location and tidal behavior Kilauea Stream mouth and Kilauea Bay are included in Class A coastal waters. There appear to be no analyses to indicate whether the quality of water in either meets the standards for this class.

Kalihiwai Stream and Bay

Kalihiwai Bay, on the north coast of Kauai (Fig. 14), is the drowned lower portion of the valley of Kalihiwai Stream, cut into post-erosional lavas. The stream itself is tidal for about a mile of its lower coast. The mean natural flow of the stream is about 30 mgd. However, the low flows of the stream are diverted inland for irrigation and the dry-weather flow of the estuary is very small.

The headwaters of the Stream are in forest lands. Downstream, the valley passes through ranch lands, and, on its east edge, cane lands.

The village in the lower valley was heavily damaged by the tsunami of 1946 and 1957. Few houses remain. These are served by cesspools. The beach at the head of the Bay is composed of calcareous sand (Moberly and Chamberlain, 1964) and the Bay is floored by sand.

The Kilauea sugar mill, located at the town of Kilauea, discharges its waste water containing mud and trash to a short valley which reaches the sea about a mile east of Kalihiwai Bay. During the harvesting season there is always a mud plume offshore, and the cane trash reaches the ocean at frequent intervals. At times the trash is carried by the wind and currents to Kalihiwai Bay where it piles up on the beach although the disposal practices do not appear to have detrimental effects on either

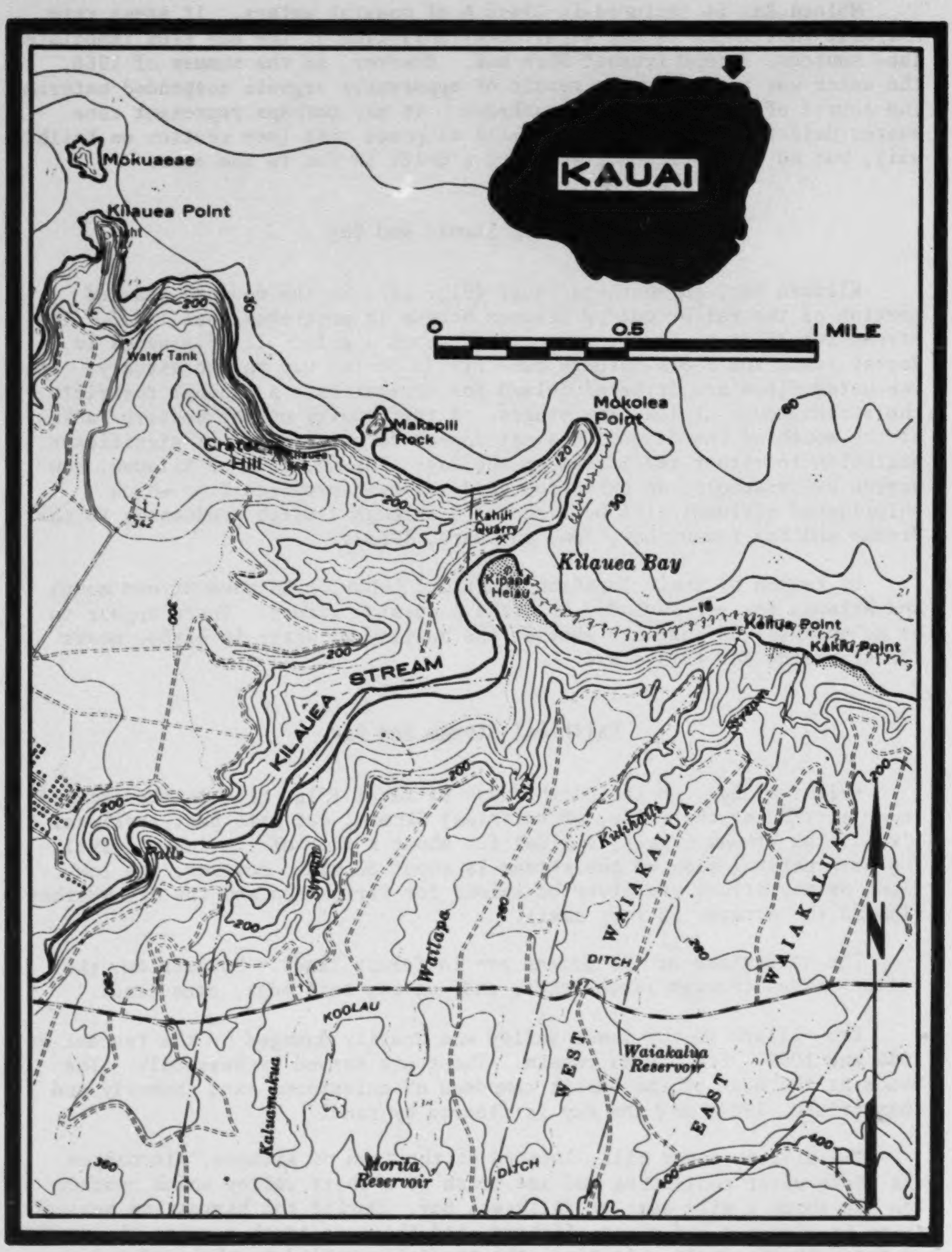


FIGURE 13. KILAUEA STREAM AND BAY.

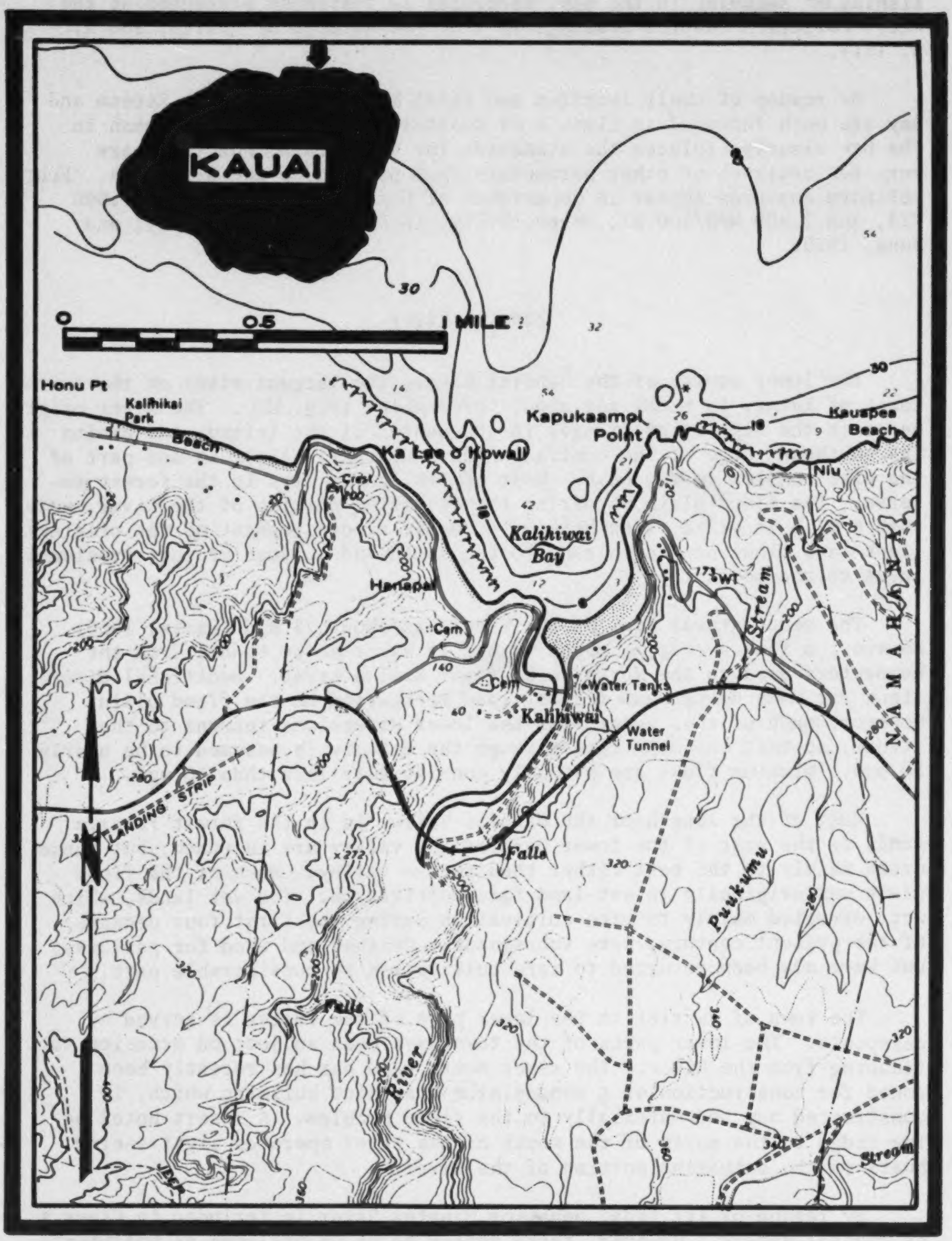


FIGURE 14. KALIHIWAI STREAM AND BAY.

fishing or swimming in the bay, according to testimony presented at the Water Pollution Control hearings in 1967 (Department of Health, 1967a, p. 161).

By reason of their location and tidal behavior Kalihiwai Stream and Bay are both included in Class A of coastal waters. The cane trash in the Bay clearly violates the standards for this class, but there are very few analyses of other parameters that pertain to the standards. Four coliform analyses appear in Department of Health records, 2,400, 7,000 <23, and 2,400 MPN/100 ml, respectively, in February, March, May, and June, 1959.

Hanalei River

The lower course of the Hanalei River, the largest river on the north coast of Kauai, is tidal for about three miles (Fig. 15). The River originates in the high-rainfall area in the center of the island, and drains the northeast edge of the central caldera near Mt. Waialeale and part of the dike complex to the east. Most of its length lies in the forest reserve. The flood plain bordering the estuarine portion of the River, more than a mile in width, lies between a deeply eroded remnant of the original flank lava flows of the volcano to the south and a ridge of post-erosional lavas to the north.

The mean natural flow of the River was about 75 mgd (Davis, 1960). However, a flow averaging about 25 mgd is exported by tunnel from the headwaters area to the North Fork of the Wailua River. Additional diversions are made downstream for wet-land irrigation on the flood plain. However, much of this water from the lower diversions returns to the stream, so that the mean flow through the estuary is assumed to be nearly 50 mgd. Minimum flows are probably considerably less than 10 mgd.

Most of the length of the Hanalei Valley is in the forest reserve. Lands to the east of the lower part of the valley are in ranch, but these drain mainly to the east rather than to the valley. Much of the flood plain was originally in wet-land taro cultivation. The wet lands, which were diverted mainly to rice cultivation during the first four decades of the present century, were subsequantly drained and used for pastures, but have now been returned to taro cultivation in considerable part.

The town of Hanalei in the lower part of the Valley is served by cesspools. The lower parts of the town have been subject on occasion to flooding from the River. The river-mouth sand bar has recently been zoned for construction of a condominium apartment building which, if constructed may add materially to the flood problem. A resort hotel on the ridge to the north of the mouth of the river operates sight-seeing boats on the estuarine portion of the River.

By reason of its tidal behavior Hanalei River is included in Class A of coastal waters. However, there appear to be no analyses of pollutants that indicate whether it meets the standards for this class.

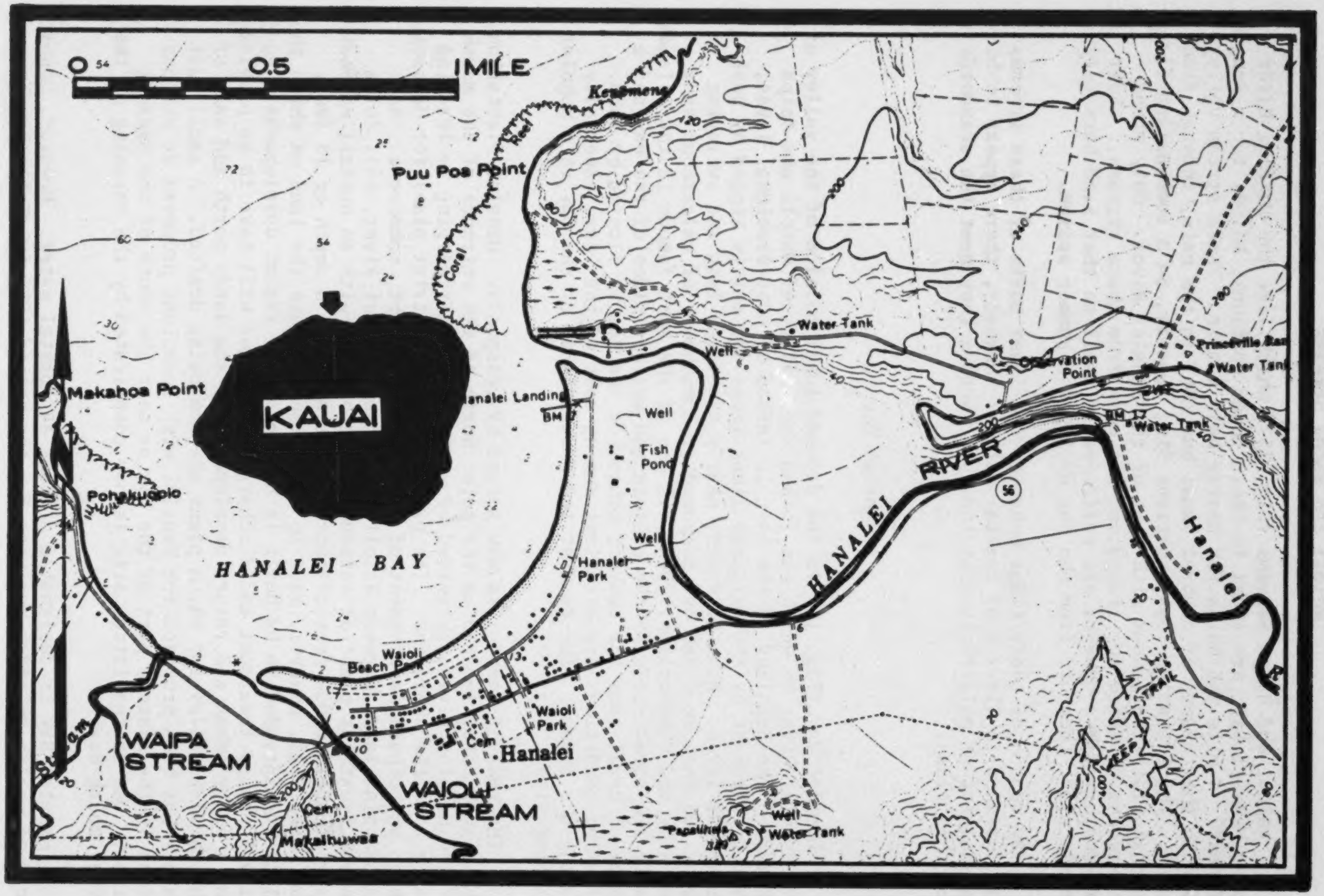


FIGURE 15. WAIOLI AND WAIPA STREAMS AND HANALEI RIVER AND BAY.

Waioli and Waipa Streams

Waioli and Waipa Streams (Fig. 15), which like the Hanalei River enter Hanalei Bay, are tidal in their lower portions, Waioli for a length of nearly a mile and Waipa for nearly half a mile. These stream valleys head in the caldera of central Kauai but cut, in the main, through flank lavas. The estuarine lower portions lie, however, in a combination flood-coastal plain continuous with that of the Hanalei River. Only minor diversions of water for irrigation are made from these streams. Their dry-weather flows however are sufficiently small so that sand bars very nearly close them off from the Bay during the summer season.

By reason of their tidal behavior the lower parts of these streams are included in Class A of coastal waters. However, there appear to be no analyses of pollutants that indicate whether they meet the standards for this class.

Hanalei Bay

Hanalei Bay (Fig. 15) is the drowned lower portion of the valley of the Hanalei River to which was joined the valleys of Waioli and Waipa Streams. The headland to the east is formed of post-erosional lavas, that to the west by the original flank lavas and merely tipped by post-erosional lavas. Hanalei Beach, nearly two miles long and averaging about 125 feet in width and composed predominantly of calcareous sand (Moberly and Chamberlain, 1964), is one of the most famous in the Islands. There are coral reefs at the eastern and western sides of the Bay and a patch of coral near the center; otherwise the Bay is floored by sand. Swimming conditions are excellent during most of the year, especially during the summer. The reef at the eastern side of the Bay is a popular surfing site.

The town of Hanalei is now served by cesspools. Hanalei Plantation, the resort hotel located on the point north of the entrance of the mouth of the Hanalei River, is served by septic tanks discharging to leaching wells near the shoreline. The proposed sewer district plans for Hanalei, which anticipate development of 165 acres of resort, commercial, and residential lands between Waioli Stream and Hanalei River, call for a sewage treatment plant of extended aeration type with an outfall extending approximately 1,000 feet offshore into the Bay to a depth of 18 feet. The plans will, however, have to be revised because the land on which the plant was intended to be built is now zoned for resort development. Additional sewage treatment and discharge facilities will have to be provided for a major urban and resort development on the lands north and east of the Hanalei valley for which plans are now being drafted. A small-boat harbor has been proposed for Hanalei with locations proposed at various times in the western part of the Bay or near the mouth of the Hanalei River. Use of the latter site is now complicated by the rezoning of the river-mouth bar.

Hanalei Bay is designated a Class AA coastal water. However, Department of Health coliform analyses for the period 1959-69 (Table 5) show medians of 620 MPN/100 ml and upper decile values of 7,000 MPN/100 ml at both the County Park and the old landing on the beach. These greatly exceed the standards for Class AA and the upper deciles exceed the standard even for Class A waters.

During flood periods, of course, Hanalei River and Waipa and Waioli Streams introduce large amounts of muddy water to the Bay, but the time constant for flushing of the Bay appears to be only a few days. Occasional concentrations of phosphorescent plankton may perhaps be related to the delivery of nutrients to the Bay by the streams. The rare observation of some small "stinging" plankton may have a similar cause. An unquestionable reduction in the population of edible fish in the Bay is probably related to heavy pressure on the nehu by tuna fishing boats rather than to any pollution cause.

Lumahai River

The Lumahai River (Fig. 16) has a tidal length of something less than a mile. The head of the Lumahai valley is deep in the central caldera in the rainy portion of the island. The seaward part of the valley, which was cut deep in the flank lavas and subsequently submerged, has been filled in part by post-erosional lavas and subsequently by sediments so that there is no longer a bay estuary. There is, however, an exceptionally broad calcareous beach, which in the dry season extends so as to restrict greatly the mouth of the river. The mean flow of the River is about 77 mgd, the median nearly 35 mgd, and the minimum about 13 mgd. There is no significant diversion of water. The flood plain is used mainly as a ranch. The valley is practically unoccupied; the few houses are served by cesspools. It is unlikely that there is significant pollution of the River.

Wainiha River

The lower course of the Wainiha River (Fig. 16) is tidal for a little more than half a mile in length. Like the Lumahai valley, the Wainiha valley heads deep in the central caldera of the volcano in the rainy part of the island, cuts across flank lavas and has been partially filled with post-erosional lavas and sediments so that Wainiha Bay is only a shallow indentation of the coast. The mean flow of the River is 185 mgd (Davis, 1960). An average of 42 mgd is diverted for hydroelectric power generation but returned to the river. Some additional water is diverted for taro irrigation, but the consumptive use is small. The median flow is over 40 mgd and the minimum more than 10 mgd. Part of the valley is used as a cattle ranch and taro is grown on the flood plain near the estuarine portion. The village of Wainiha is served by cesspools. The beach which separates the estuarine portion of the River from the Bay is composed of sand,partly of calcareous and partly of terrestrial origin.

Although Wainiha Bay has been designated a Class AA coastal water, the River is presumably in Class A. There appear to be no analyses, however, that indicate whether it meets the standard for this class.

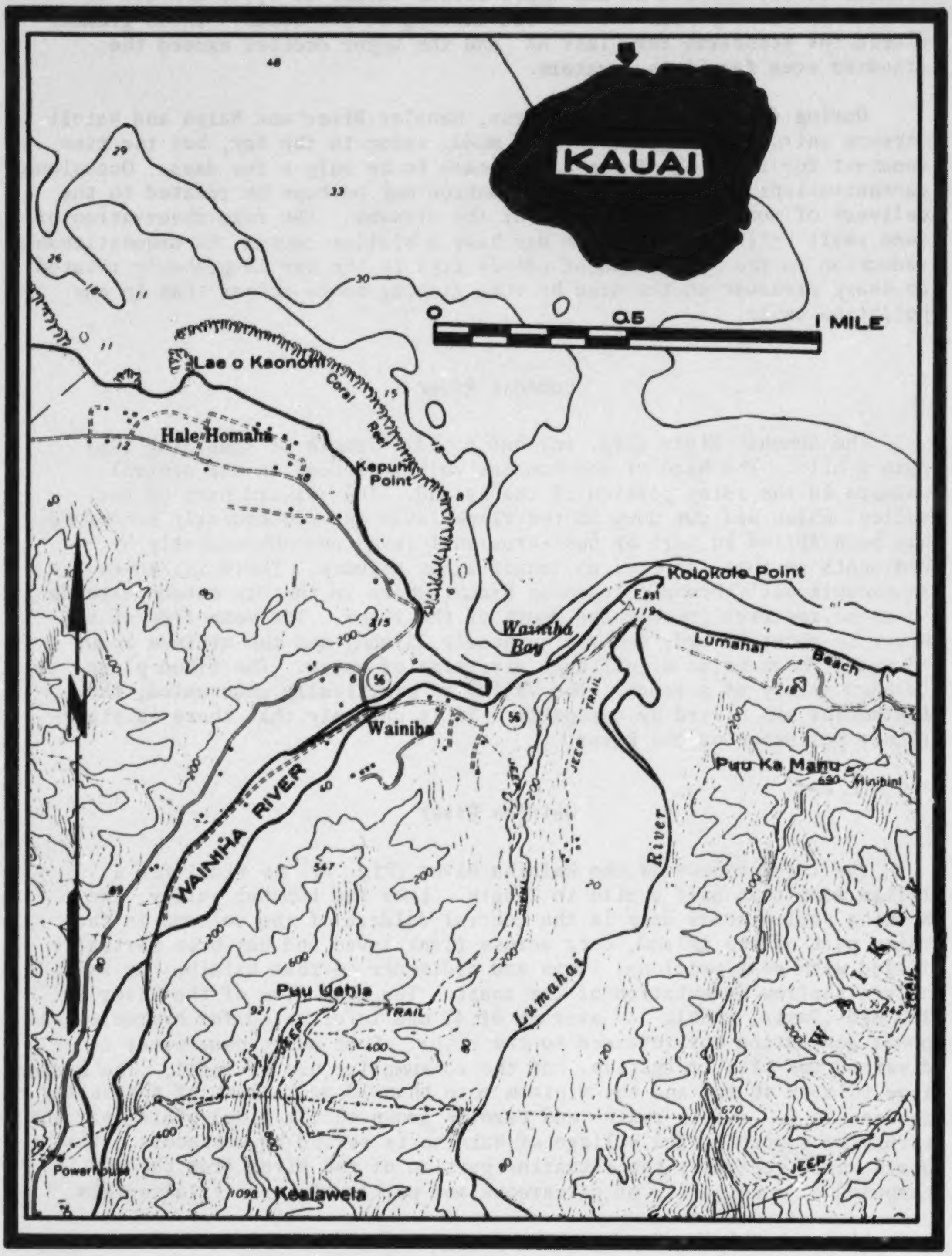


FIGURE 16. LUMAHAI AND WAINIHA RIVERS.

OAHU

The island of Oahu consists of the tops of two shield volcanoes, the older Waianae volcano to the southwest and the younger Koolau volcano to the northeast (Stearns and Vaksvik, 1935; Stearns, 1939, 1940a). The Waianae volcano is structurally quite complex and has been very deeply eroded. The Koolau volcano has also been extensively eroded, especially at its east end. The island has been deeply submerged, and extensive coastal plains, protected by coral reefs, have developed along most of the coastline. Post-erosional volcanics are interbedded with the sediments of the coastal plains and valley fills and in some places have extended the coastline.

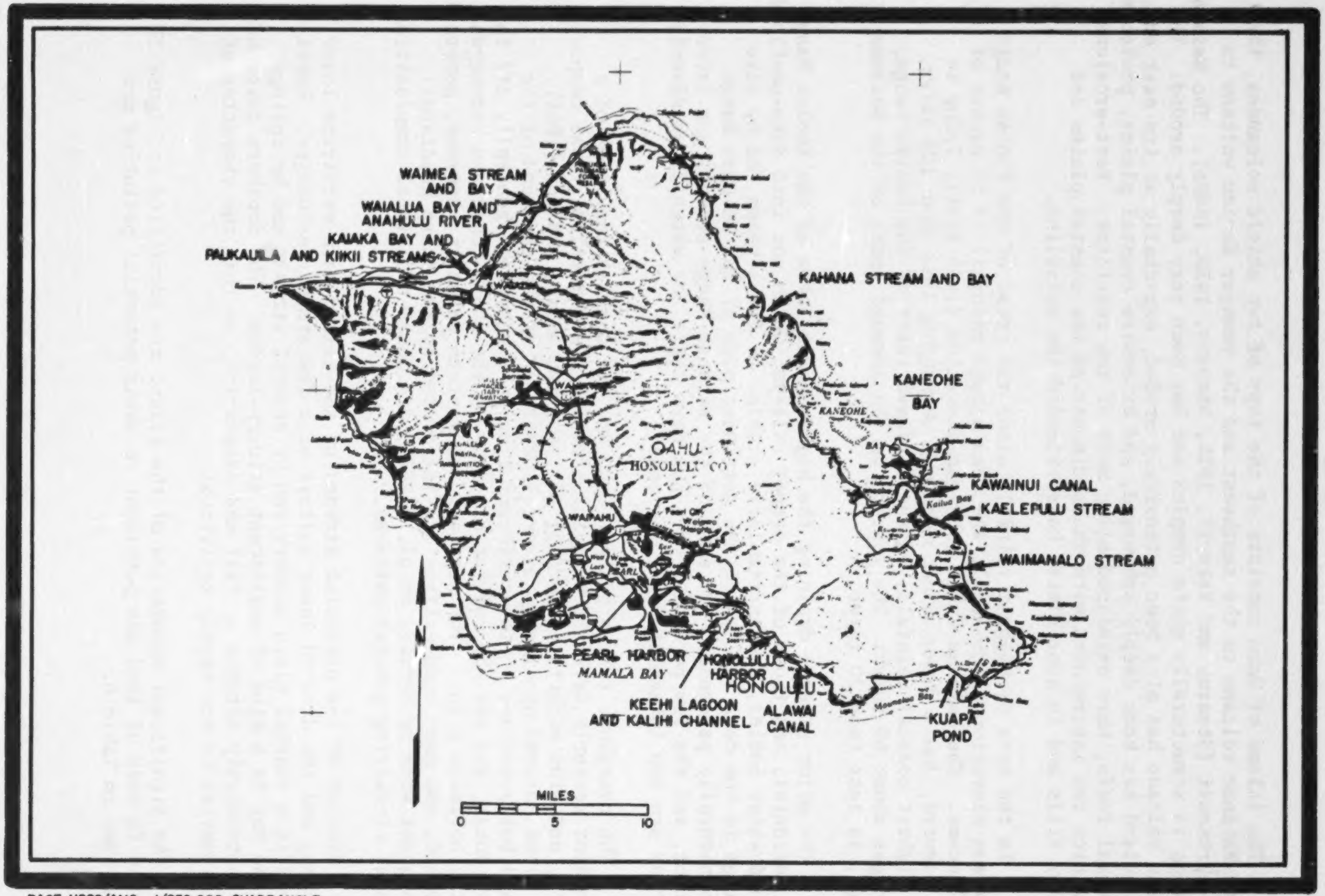
In the area of highest rainfall along the crest of the Koolau Range (maximum elevation 3,105 feet), the mean annual rainfall is in excess of 250 inches. The Waianae Range (maximum elevation 4,025 feet), lying to the leeward, has a lower crest rainfall, averaging less than 100 in/yr. The highest coastal rainfall, on the windward coast of the Koolau Range, averages about 60 in/yr. The lowest, on the leeward coast of the Waianae Range, is less than 20 in/yr.

The major streams draining the high-rainfall area of the Koolau Range are perennial, and those of the deeper valleys, which cut into dike-confined ground-water bodies, are particularly stable. A few streams fed by dike springs in the deep valleys on the northwest side of the Waianae Range were naturally perennial, but most of the Waianae Range streams are intermittent, and the few perennial ones now have their low water flows diverted so they are now intermittent at the coast.

The nearshore currents about Oahu are the complex resultant of a permanent westerly drift of changing strength and direction, tidal components, and wind effects, according to Laevastu, Avery, and Cox (1964). The flood current apparently diverges generally at the east end of the island,but sometimes on the northeast side, and converges generally off the south coast, and the ebb current diverges on the south coast and converges at the northern point. The set past the western point is, however, generally westward, and many complexities are introduced by the sharp headlands. Subsequent work by Wyrtki, *et al.* (1967), has shown additional complexities without clarifying general patterns.

Several of the perennial streams of the island have estuarine lower reaches, and the drowned lower valleys of a few are bay estuaries. Pearl Harbor is a coastal plain estuary fed by several streams and by springs. Kaneohe Bay is a kind of coalescent estuary-lagoon. The southern coast has been extensively altered by fill and excavation, so that the character of its estuaries is now mainly artificial.

The significant esturaries of the island are identified in Figure 17 and the factors of land use pertinent to their potential pollution are summarized in Table 6.



BASE: USGS/AMS 1/250,000 QUADRANGLE

FIGURE 17. ESTUARIES ON THE ISLAND OF OAHU.

TABLE 6. ESTUARIES OF OAHU AND THEIR POTENTIAL POLLUTION.

ESTUARY SYSTEM	BAY ESTUARY	STREAM ESTUARY	WATER DEVELOP-MENT	AGRICULTURAL DEVELOPMENT	INDUSTRIAL DEVELOPMENT	URBAN DEVELOP-MENT	ESTUARY DEVELOPMENT
PEARL HARBOR	PEARL HBR		I[1]	S, P, R	S, E, M	S	H, O_B, O_P, F_P, F_B
KEEHI		MOANALUA STR			M	S	
		KALIHI STR			M	S, C	
	KEEHI LGN				M		H, S, R
HONOLULU		KAPALAMA CNL			P, M	S, C	
		NUUANU STR				S, C	
	HONOLULU HBR				M, R, E	S	H, (O_R)[2]
ALA WAI	ALA WAI HBR	ALA WAI CNL				S, C	S, R
KUAPA	KUAPA POND					S, C	S, R
KAELEPULU		KAELEPULU STR				S, C	R, O_S
KAWAINUI		KAWAINUI CNL		R		S, C	R, O_S
KANEOHE	KANEOHE		I	B, R, M	M	S, C	S, R, F_B, F_S, F_P, O_P, O_S
KAHANA		KAHANA STR	I	S, R		C	R
	KAHANA						R
WAIMEA		WAIMEA R	I	S, R		C	
	WAIMEA						R
WAIALUA		LOCO EA	I	S, R		C	F_P
		ANAHULU R	I	S, R, P		C	
	WAIALUA						S, R
KAIAKA	KAIAKA	PAUKAUILA STR	I	S, T, R, P		C	
		KIIKII STR	I	S, R, P		C	

[1] REFER TO PAGES 18 - 20 FOR THE KEY TO THESE SYMBOLS.

[2] THE OUTFALL FROM THE HONOLULU SEWER SYSTEM DISCHARGES TO THE OCEAN OFF SAND ISLAND RATHER THAN INTO THE HARBOR.

Pearl Harbor

Pearl Harbor, in southern Oahu, is a true coastal plain estuary (Plate 1). Its three lochs represent the drowned valleys of three major streams which crossed the southern coastal plain of Oahu and united to form a single river flowing to the sea in the valley that is now flooded to form the main channel. The lochs have been considerably altered in shape by marine erosion and sedimentation. The geologic history of the harbor has been outlined in detail by Stearns and Vaksvik (1935).

Pearl Harbor became a United States naval base by treaty at the time of the Hawaiian Kingdom. It is the headquarters for the 14th Naval District, and includes the Pearl Harbor Naval Shipyard. The harbor has been improved by dredging a number of times, notably in the 1930's. The peripheral lands have now mostly been acquired by the Navy although portions are under lease for sugar-cane cultivation and other uses.

Pearl Harbor is Hawaii's major source area for nehu (*Stolephorus purpureus*), the principal bait fish used by the aku (tuna) fishermen. It serves as spawning, nursery, and rearing grounds for the nehu. According to David Buchard, Planning and Development Coordinator for the Hawaii Department of Land and Natural Resources, "During 1965 the production of aku exceeded 16 million pounds of fish with an ex-vessel value of over 2 million dollars. To achieve this production, the aku fishermen captured 36,384 buckets of bait fish of which 35 percent or 12,696 buckets of bait were taken from Pearl Harbor" (Department of Health, 1966). There is a large number of fishponds around the margins of the harbor, and the harbor was once the site of intensive bait fishing. Oysters, once of edible quality (Commission of Fish and Fisheries, 1901) grow in the harbor but were never a source of much income.

Except in the vicinity of Hammer and Keahi Points east of the mouth of the entrance where there is a military residential development, both sides of the main entrance are in military-industrial use, as are both sides of the channel to Middle and East Lochs, Ford Island, and the east shore of East Loch. Sugar cane is grown on the south shore of West Loch, and the head of the Waipio Peninsula. Pearl City Peninsula is urban (mainly military), and the lands at the heads of all the Lochs are mainly urban, much of it industrial, and part of it military.

The natural fresh surface-water supply of the harbor is derived from eight streams which represent tributaries of the original loch-valleys: Honouliuli and Waikele entering West Loch, Waiawa entering Middle Loch, and Waiau, Waimalu, Kalauao, Aiea, and Halawa entering East Loch. Of these streams, Honouliuli and Aiea are intermittent. The perennial streams all have their headwaters in forest reserves in the high-rainfall area of the Koolau Range. All drain lands in sugar cane on their way to the sea and Waikele drains lands in pineapples as well. All pass through highly urbanized areas close to the harbor. Several of these streams, notably Waikele, Waiawa, Waimalu, Kalauao, and Halawa, are themselves estuarine for short distances from the harbor.

The flows of the streams are gaged at various points, but the gaging involves both governmental and private agencies, and because there are diversions from all for irrigation, importations of water to the area from the windward side of the range, and additions to the flow of some from basal springs, it is difficult to obtain complete data on either natural flow characteristics or the flow characteristics as the streams enter the harbor under present conditions. The latter characteristics are best indicated by a series of gages installed at low elevation by the U. S. Geological Survey, some of which have only very short records. The data are summarized in Table 7.

TABLE 7. STREAM FLOW TRIBUTARY TO PEARL HARBOR.
ESTIMATES FROM U. S. GEOLOGICAL SURVEY, 1964.

LOCH	STREAM	MINIMUM FLOW (MGD)	MINIMUM FLOW (MGD)
WEST	WAIKELE	26	6
MIDDLE	WAIAWA	16	2
EAST	WAIMALU	5	0
	KALAUAO	1	0
	HALAWA	8	0
TOTAL		56	8

The discharges of the streams are supplemented by flows of five large springs representing the discharge of an immense fresh ground-water body floating on and displacing salt water in the lava-flow bedrock of the island. The springs emerge from the toes of bedrock ridges between the streams, where the coastal plain sediments have been stripped off or thinned by wave erosion. The Waikele Spring flows to West Loch, the Waiawa Springs to Middle Loch, and the Waimano, Waiau, and Kalauao Springs to East Loch.

Some of the discharge from the springs is diverted for taro and watercress irrigation, whose consumptive use is small, and additional amounts are pumped inland for sugar cane irrigation. The flow of the Waiau and Waimano Springs is used for cooling in the Hawaiian Electric Company Waiau power plant, and a part is then boosted inland for sugar irrigation. Visher and Mink (1964) have found that the discharges of these springs have a nearly linear relation to the head in the Pearl Harbor aquifer. Average flows for the period 1953-57, minimum flows extrapolated from the Visher-Mink relations to the record low-head period of 1945, and minimum flows after diversion estimated by Visher and Mink for a low-head period in 1954 are shown in Table 8.

TABLE 8. SPRING FLOW TRIBUTARY TO PEARL HARBOR.
AFTER ESTIMATES BY VISHER & MINK (1964).

LOCH	SPRING	MEAN FLOW (MGD)	1946 MINIMUM FLOW (MGD)	1954 MINIMUM FLOW BEFORE DIVERSION (MGD)	1954 MINIMUM FLOW AFTER DIVERSION (MGD)
WEST	WAIKELE	22	5	7	6
MIDDLE	WAIAWA	14	11	11	7
EAST	WAIMANO-WAIAU	32	21	22	10
EAST	KALAUAO	19	14	15	8
	TOTAL EAST LOCH	51	35	37	18
GRAND TOTAL		87	51	55	31

In addition to the flows of the springs and streams, there is some waste to the harbor from artesian wells watering wet-land crops, estimated by Visher and Mink (1964) at 5 mgd, and there is probably a significant quantity of shallow ground water entering the harbor by seepage from coral and other aquifers. In total, the "fresh" water supply (much of it quite brackish by domestic water standards), exclusive of waste disposals, entering the harbor in a dry period, may be estimated as follows:

Source	Flow, mgd
Streams	8
Springs	31
Wells	5
Shallow aquifers	6+
Total	50 mgd

During rainy periods not only are the flows of the perennial streams greatly increased, but the intermittent streams flow, and the diversion of spring water for sugar irrigation is stopped. Hence, the mean flow to the harbor is considerably greater than the mean flow of the perennial streams plus spring, well, and seepage flow, probably considerably more than 100 mgd.

Only very meagre current observations are available for Pearl Harbor.

> "A survey by Austin, Smith and Associates (1961) in Middle Loch off Pearl City, using surface and subsurface floats, indicated the existence of weak but well defined tidal components. The flood, corresponding in phase to the rising tide, set generally northwest towards the head of the Loch, and the ebb, corresponding in phase to the falling tide, generally set southeast toward Ford Island. Superimposed on the tidal oscillations, which involved velocities only on the order of a tenth or tenths of a knot, were a prevailing seaward flow on the surface resulting from stream and spring discharge and wind drag (Laevastu, Avery, and Cox, 1964).
>
> In another survey made at the harbor entrance by Austin, Smith and Associates (1960), involving surface and subsurface floats, the flood current was shown entering the harbor with a velocity on the order of 0.2 knot, generally with the tide rise as expected (Laevastu, Avery, and Cox. 1964)."

However, Au in 1965, using a current cone, found an outgoing surface current of 0.95 knot.

The problem of pollution in Pearl Harbor is an old one. A traditional mele (Hawaiian song) had this verse (Emerson, 1909):

O Ewa, aina kai ula i ka lepo	Ewa's lagoon is red with dirt
I ula i ka makani anu Moa'e	Dust blown by the cool Moa'e
Ka manu ula i ka lau ka ai	A plumage red on the taro leaf
I palahe'a ula i ke kai o kuhi'a	An ocherous tint in the bay

However, the natural pollution by sediment, whether wind blown, as above, or stream transported, is slight compared with the combination introduced by accelerated sedimentation and urban and industrial sewage disposal. Even as late as the years immediately prior to World War II, the waters of Pearl Harbor could be used for yachting, fishing, shell fishing, and some swimming (Division of Sewers, 1958).

The primary sources of pollution in Pearl Harbor are sanitary sewer outfalls of the City and County of Honolulu and the U. S. Navy, sugar mill waste-water discharges, ships using the harbor, storm-sewer discharges, cesspool seepage, and high-temperature discharge from the Hawaiian Electric Company power plant. The Division of Sewers in "A Report on Sewerage Master Plan for Waipahu, Ewa, Oahu," (1957) listed 69 outfalls by actual count on the shorelines of East Loch and estimated that there were over 100 outfalls in total. Many of these outfalls carried sewage from naval installations.

The South Avenue sewer outfall (3.5 mgd est.) discharges raw sanitary sewage collected from Hickam Air Force Base and surrounding Naval housing developments. The Halawa primary treatment plant (0.49 mgd) and the Pearl City primary treatment plant (2.55 mgd) both discharge through outfalls directly to the Harbor. Approximately 0.5 mgd of raw sewage from Aiea is dumped into a stream which discharges outfalls into Aiea Bay, East Loch, Pearl Harbor.

Approximately 2.5 mgd of raw sewage from the town of Waipahu, mixed during the harvesting season of eight or nine months with 2 to 2.5 mgd of waste water from the sugar mill of Oahu Sugar Company at Waipahu, is used for irrigation on Waipio Peninsula (Humme, Department of Health, 1966b). When no irrigation is required, for example during wet weather, the raw sewage is discharged to West Loch through an outfall on the west shore of the Peninsula.

Approximately 10 mgd of nearly-fresh spring water and some well water are used by Hawaiian Electric Company for cooling in the older unit of its Waiau Power Plant (R. H. Dale, U. S. Geological Survey, personal communication). The newer units use a maximum of 336,000 gpm and a minimum of 128,000 gpm of salt water from the harbor. Intake temperatures range from 78° to 84°F. Discharge temperatures have a maximum increase of 10°F and a minimum increase of 2°F.

The effects of these discharges are generally inadequately documented. Away from the discharge point of the thermal water from the Waiau Power Plant the surface temperature decrease to 87°F at a distance of 500 feet, 82°F at 1,000 feet, 80.9°F at 3,250 feet, and 79.6°F at 5,250 feet (Larsen, 1968).

The water of West Loch has a distinctive red cast to it, which is especially pronounced after any heavy rain due to soil washed in from surrounding lands (Humme, Department of Health, 1966b), but which persists between times at the head of the Loch.

In "A Report on Sewerage Master Plan for Waipahu, Ewa, Oahu" (1957), the Division of Sewers included a list of indices of Pearl Harbor water samples. The dissolved oxygen ranged from 6.0 to 8.2 ppm, the average biochemical oxygen demand varied between 1.1 and 4.0 ppm, and coliform bacteria ranged from 13 to 130,000 MPN/100 ml. Generally the coliform count was lowest near the entrance of the Harbor (240 MPN/100 ml) and highest in the stream mouths (Waimalu Stream mouth: 130,000 MPN/100 ml; Waiawa Stream near mouth: 24,000 MPN/100 ml). The average biochemical oxygen demand followed the same pattern with inverse values, *i.e.*, the higher values were closer to the entrance of the Harbor.

Austin, Smith and Associates and Metclaf and Eddy Engineers (1962) found the biochemical oxygen demand in Middle Loch to vary systematically from 2.8 ppm near Ford Island to 0.2 ppm at the harbor entrance, the dissolved oxygen content to range from 5.2 ppm to 0.8 ppm without apparent systematic geographic variations, and the coliform concentration to range from 62 to 70,000 MPN/100 ml.

In 1965 a limited study was made of pesticide concentrations in the waters of Waikele Stream and West Loch, the bottom mud, and the oysters (Klemmer, 1965-66). The results are summarized in Table 9. The maximum concentrations observed in the waters are on the order of 1/10 to 1/20 the concentrations reported as affecting oysters to the extent of 50 percent reduction in shell growth rate (Butler, 1962, 1965).

TABLE 9. PESTICIDE RESIDUES IN PEARL HARBOR WATER, MUD, AND OYSTERS.*

SAMPLE DESCRIPTION	SAMPLE NO.	PESTICIDE RESIDUES (PARTS PER BILLION)				
		P,P' DDT	O,P' DDT	DDE	DDD	LINDANE
FRESH WATER	1	0.06	-	0.09	-	-
	2	0.02	-	0.04	0.02	0.12
	3	-	-	TRACE	-	-
MARINE BRACKISH	1	0.04	-	0.06	-	-
	2	0.02	-	0.02	0.02	0.10
BOTTOM MUD	1	0	0	1.00	1.00	0
	2	0	0	1.00	2.00	0
	3	0	0	1.00	2.00	0
OYSTERS —						
WAIKELE STREAM		12.00	5.00	33.00	24.00	1.00
WALKER'S BAY		15.00	6.00	33.00	25.00	3.00

* (FROM COMMUNITY STUDIES ON PESTICIDE, 1965-66.)

Coliform counts in the vicinity of the oyster beds were found by Sparks (1963) and Sakuda (1966) to range from 670 to 2,400,000,000 MPN/100 ml. The oysters themselves contained coliform concentrations varying from 2,300 to 24,000,000 MPN/100 ml. A fish kill involving 200 fish, mainly of forage and trash species, was reported in a four-acre area in East Loch in August 1960. The kill was attributed to domestic sewage. A second kill in the same year involved mainly game fish. The exact location of the mile-wide area in the harbor was not specified. The source of pollution in this case was not determined. A fish kill occurring in Kalauoa Stream in 1965 and involving an estimated 1,000 game fish was attributed to poisons (herbicides, insecticides, etc.) (FWPCA, 1961, 1966).

A dermatitis, the "Pearl Harbor itch," caused by some as yet unidentified marine organism, has been reported by swimmers and waders in the West Loch of Pearl Harbor (Arnold and Bonnet, 1950; Chu and Cutress, 1954).

The head of West Loch has been designated a Class AA coastal water and the remainder of the harbor as a Class B water. The coliform concentrations in West Loch, and probably the silt concentration as well, greatly exceed Class AA standards. Quite probably the fecal coliform concentrations and possibly other pollution parameters exceed even Class B standards at places in the rest of the harbor.

Kalihi Channel and Keehi Lagoon

The southern Oahu shore from the Pearl Harbor entrance eastward to Waikiki is almost entirely artificial as may be seen by a comparison of the Geological Survey topographic maps of 1917 and 1954 (Figs. 18 and 19). The Kalihi Channel was originally a shallow channel across the reef through

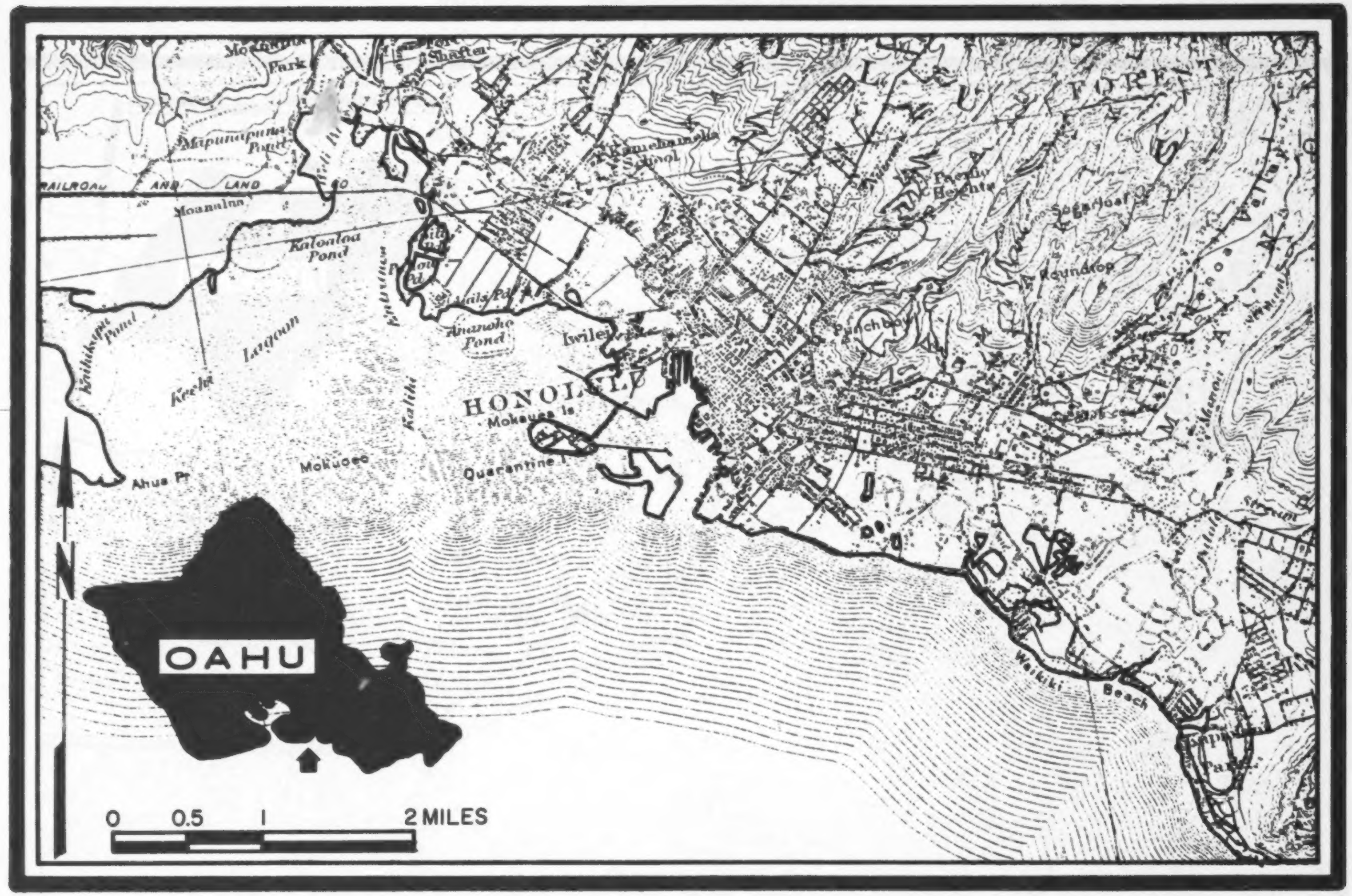


FIGURE 18. HONOLULU COAST IN 1913.

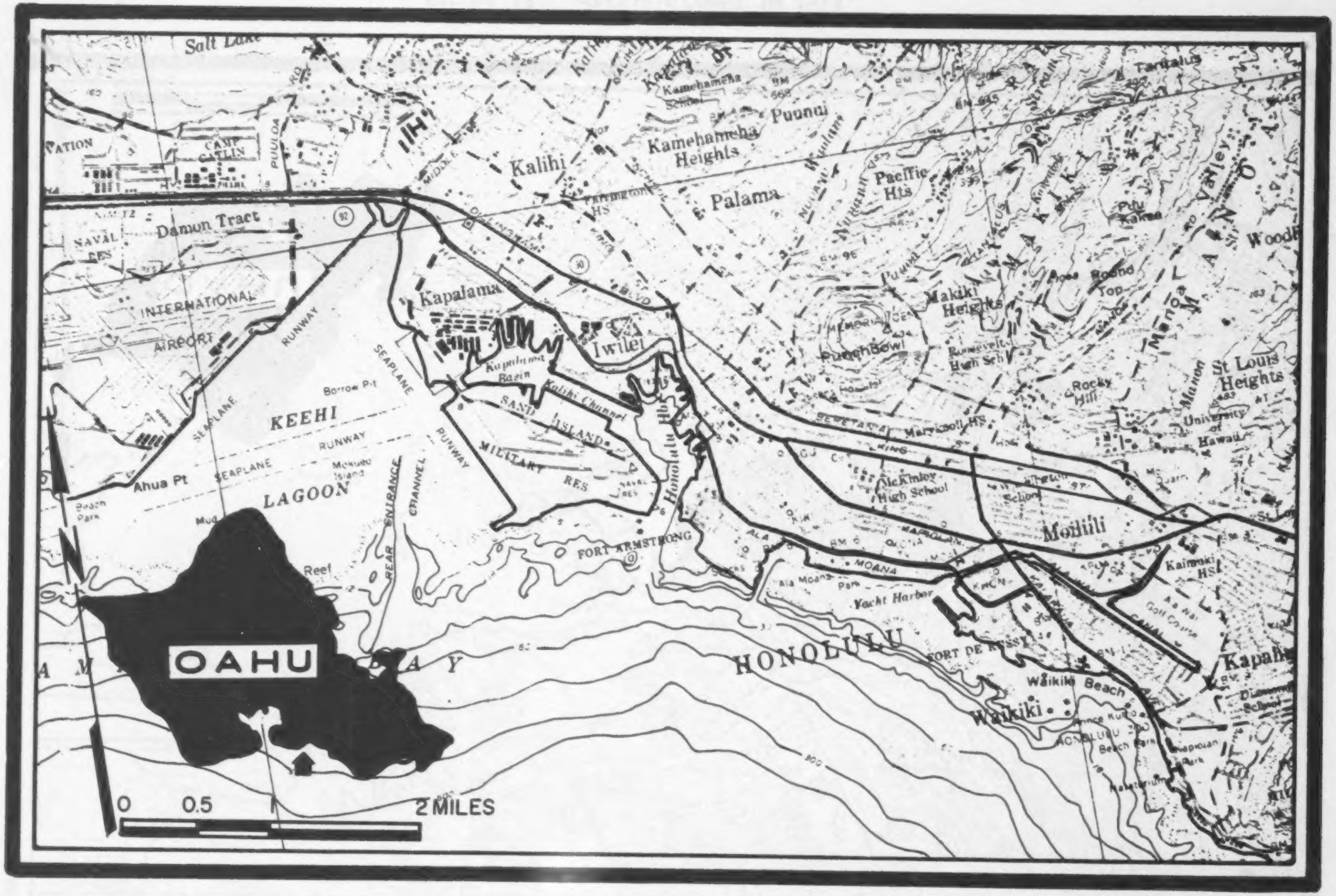


FIGURE 19. HONOLULU COAST IN 1954.

which the waters of Moanalua and Kalihi Streams made their way to the sea. It was connected on the east with what is now the Kapalama Basin and, by shallow water only with Honolulu Harbor beyond, and connected on the west with Keehi Lagoon, which was almost entirely surrounded by reef. Much of what is now Honolulu Airport was originally reef, the shoreward part of Keehi Lagoon, other ponds, and salt marshes. Material dredged from the seaplane runways in and extending west from the original lagoon was used as fill for the airport and the shoreward margins of the lagoon. Additional material dredged from the present Kalihi ship channel was used also for fill in originally marshy areas and fish ponds. Although the present channels are much deeper than the original ones, both the water area and the tidal prism of the lagoon have been greatly restricted (Fig. 20).

Both Moanalua and Kalihi Streams head in the forest reserve areas in the high-rainfall belt along the summit of the Koolau Range. Their bedrock valleys, eroded far below present sea level, are filled with alluvium and, in the case of Kalihi, post-erosional lavas. Moanalua Stream, upon emerging on the coastal plain fronting bedrock ridges, is diverted south by the part-erosional Salt Lake tuff crater. The lower portions of the streams, artificially channelized, are estuarine. The bottoms of both valleys, especially that of Kalihi, have been developed as residential areas of Honolulu as have tributary valleys and the ridges between. Part of these areas are still served by cesspools, although most are now connected with the Honolulu sewer system discharging through an outfall at Sand Island, to the east of the Kalihi ship channel.

Mean and minimum discharges of the two perennial streams at the gaging stations as given by the U. S. Geological Survey (1961) are shown in Table 10.

TABLE 10. MEAN AND MINIMUM DISCHARGES OF MOANALUA AND KALIHI STREAMS.

STREAM	GAGE ALTITUDE, FT	DISCHARGES, MGD	
		MEAN	MINIMUM
MOANALUA	339	2	0
KALIHI	464	5	< 1*

* APPROXIMATELY 0.1 MGD SPRING FLOW IS DIVERTED FOR DOMESTIC SUPPLY. THE MEAN DISCHARGES TO THE ESTUARY ARE UNDOUBTEDLY MUCH HIGHER BECAUSE OF LARGER FLOOD DISCHARGE AND THE MINIMUM DISCHARGES SOMEWHAT HIGHER BECAUSE OF ADDITIONAL SEEPAGE FROM THE COASTAL PLAIN SEDIMENTS AT LOW ELEVATION.

Current meter measurements by Bathen (Parsons Company, 1968) indicate that the effect of the tides is to create a circulation from east to west through the lagoon. The major flood-tide volume transport enters at the east end of the lagoon (through the Kalihi ship channel and in part through Honolulu Harbor and the Sand Island channel). The major ebb-tide volume transport exits by way of the seaplane runway along the shore to the west past Ahua Point. The average volume transport leaving the lagoon past Ahua Point as determined by Bathen in a two-week study was 0.95×10^6 m^3/hr.

In discussing bait fish catches, David Butchart, Department of Land and Natural Resources, stated that "In 1965, Keehi Lagoon was the second largest producer of bait fish for the aku industry while Honolulu Harbor ranked fifth.

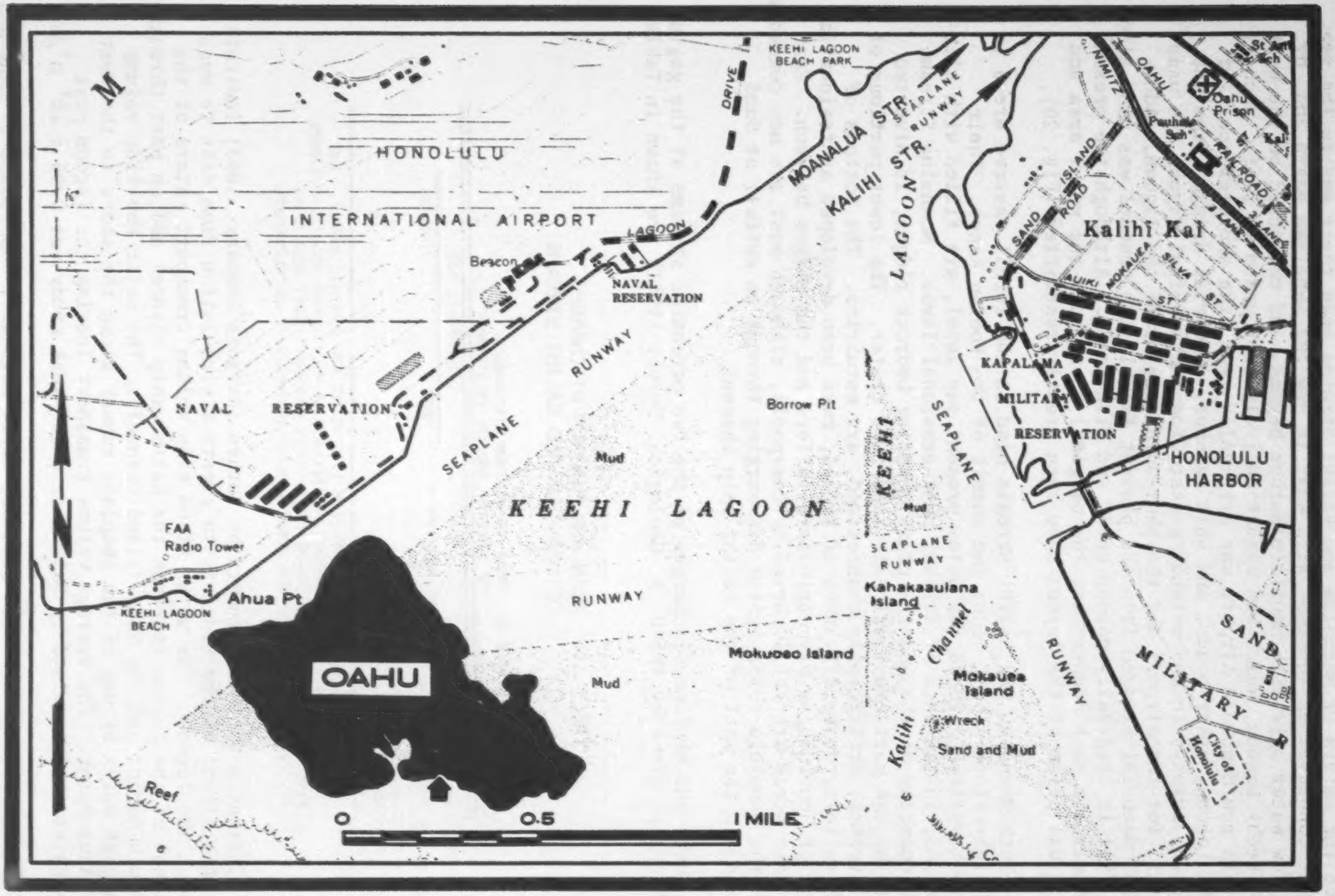


FIGURE 20. KALIHI CHANNEL AND KEEHI LAGOON

The combined bait-fish harvest of the two areas amounted to 9,300 buckets or 26 percent of the total bait-fish production in Hawaii" (Department of Health, 1966b).

The principal sources of pollution in the estuary are the urban areas through which the Moanalua and Kalihi Streams flow, and especially the industrial areas closest to the coast. A small shipyard on the east side of the lagoon probably contributes some wastes. The shacks of squatters on two sand islands flanking the Kalihi ship channel must be sources of some wastes. Some pollution is probably introduced from Honolulu Harbor via the Sand Island channel, and some may be introduced from the discharge area of the Honolulu and Fort Shafter sewer outfalls off Sand Island.

The marina area in Keehi Lagoon (actually on the Honolulu shore of the original Kalihi Channel) has been designated as Class B coastal waters. The remainder of Keehi Lagoon may be Class A waters. However, the ship channel from the Sand Island bridge to sea may be considered part of Honolulu Harbor and hence be part of the Class B waters of that harbor.

Samples from various points within the channel and lagoon have been analyzed by the Department of Health for coliform content over the period from 1962-1969 (Table 11). So far as these analyses are concerned, the waters meet the median coliform standards for Class A waters, except at the entrances of Moanalua and Kalihi Streams and Sand Island channel. The upper decile coliform standard is, however, exceeded at all stations.

TABLE 11. COLIFORM ANALYSES FOR OAHU ESTUARIES
ANALYSES BY DEPARTMENT OF HEALTH.

			MPN/100 ML				
STATION NO.	PLACE	PERIOD (YRS.)	N	MINIMUM	MEDIAN	UPPER DECILE	MAXIMUM
C-1	KEEHI LAGOON PARK	1962-68	96	0	240	7,000	70,000
D	MOANALUA STREAM MOUTH	1962-68	96	6	2,400	70,000	700,000
E	KALIHI STREAM MOUTH	1962-68	96	240	24,000	240,000	700,000
X	KEEHI PARK AND SEA-PLANE RUNWAY	1962-68	96	0	240	7,000	70,000
Y	KEEHI LAGOON PARK AND SEA-PLANE RUNWAY	1962-68	96	0	240	24,000	240,000
1	HONOLULU HARBOR ENTRANCE	1962-68	99	0	6	700	7,000
2	KEEHI LAGOON, SEAWARD SEA-PLANE RUNWAY	1962-68	100	0	240	7,000	700,000
3	KEEHI LAGOON, SEAWARD SEA-PLANE RUNWAY	1962-68	99	0	62	7,000	24,000
4	SAND ISLAND BRIDGE	1962-68	99	24	7,000	240,000	240,000
5	KEEHI LAGOON SMALL-BOAT HARBOR	1962-68	99	6	700	24,000	240,000
	KEWALO BASIN	1959-68	220	0	2,400	7,000	700,000
	ALA WAI CANAL AT ALA MOANA BLVD. BRIDGE	1959-68	218	6	2,400	7,000	240,000
	ALA WAI CANAL AT McCULLY ST. BRIDGE	1961-69	76	6	2,400	70,000	700,000
	ALA WAI YACHT HARBOR	1959-68	224	0	240	7,000	240,000
	KAELEPULU STREAM AT KEOLU BRIDGE	1957-69	130	0	700	24,000	240,000
	KAHANA BEACH PARK	1965-69	36	0	240	24,000	240,000

Tetra Tech., Inc. (Parsons Company, 1968) have found that the coliform concentrations for the stream-mouth stations are correlated with stream flow indicating that the streams are the sources of pollution. The high concentration at the Sand Island channel results, surely, from contamination from Kapalama Basin in Honolulu Harbor.

Navy analyses of coliforms between 1964 and 1968 for the beaches at Ahua Point reported by Tetra Tech., Inc. (Parsons Company, 1968), indicate that the water quality there is considerably better than the standard for Class A water.

An intensive 10-day survey of the waters from Kewalo Basin to Keehi Lagoon was made in the summer of 1968 by the Department of Health, whose results, so far as coliforms and fecal coliform counts are concerned, have been summarized by Tetra Tech., Inc. (Parsons Company, 1968). The stations are located in Figure 21, and the counts, as summarized by Tetra Tech., Inc., are shown in Table 12. During the 10-day period the fecal coliform counts in Keehi Lagoon were low, but so were the toal coliform counts as compared with the long-term record. Hence, it is doubtful that the fecal counts are representative of normal conditions.

TABLE 12. TOTAL AND FECAL COLIFORM COUNTS - FROM DEPARTMENT OF HEALTH 10-DAY SURVEY, 1968, FOR ESTUARY STATIONS. DATA ANALYZED BY TETRATECH, INC. (PARSONS, 1968).

STA. NO.	NO. OF OBS.	TOTAL COLIFORM (NO./100 ML)				FECAL COLIFORM (NO./100 ML)			
		AVERAGE	MEDIAN	MAXIMUM	MINIMUM	AVERAGE	MEDIAN	MAXIMUM	MINIMUM
1	9	13	3	81	0	39	0	260	0
18	5	12	10	30	0	2	0	10	0
19	5	4	0	20	0	0	0	0	0
20	4	32	30	60	10	15	10	40	0
21	9	6,780	0	56,000	0	3,339	0	30,000	0
22	9	12,120	170	107,000	0	11,294	50	100,000	0
23	5	66	60	118	0	1,740	1,480	4,000	0
24	5	194	110	692	0	3,468	1,135	11,000	0
25	5	644	100	3,000	0	632	10	3,000	0
26A	9	1,683,044	125,000	8,700,000	19,600	960,000	125,000	6,900,000	5,000
26B	6	4,678	5,000	9,000	0	3,168	2,500	9,000	0
27	5	164,634	370	816,000	0	160,920	400	800,000	0

Ultramar Chemical Water Laboratory made two studies in Keehi Lagoon in 1968, one during an 8-day period for the Department of Health in July (Ultramar, 1968a) and the other during a 3-day period immediately following in July and August for Tetra Tech., Inc. (Parsons Company, 1968). Both total coliform and fecal coliform counts were generally low except at a station in the east-west seaplane runway, probably receiving some of the flow from the Sand Island channel. Here coliforms on August 2 were 63,000/100 ml and the fecal coliforms 92,000/100 ml. The excess of fecal coliforms over total coliforms suggests problems with the analytical methods.

The initial values for coliform concentration in a survey of water quality around Oahu begun by the Federal Water Pollution Control Administration have also been summarized by Tetra Tech., Inc. (Parsons Company, 1968). These showed counts throughout the runway areas in excess of 2,000/100 ml on July 25, 1968 and equal to or in excess of 10,000/100 ml on July

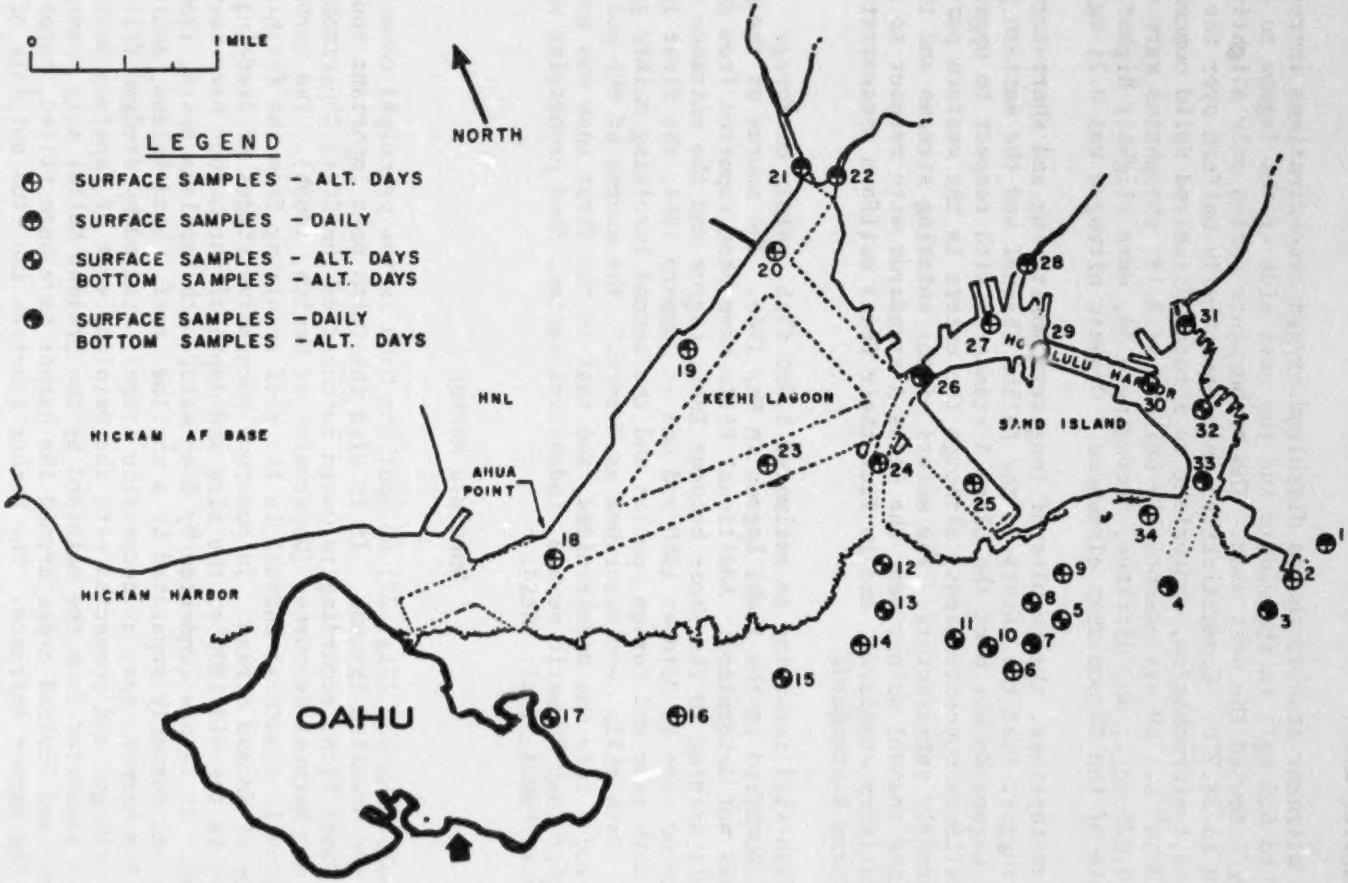


FIGURE 21. SAMPLE STATIONS OF DEPARTMENT OF HEALTH 10-DAY SURVEY, KEWALO BASIN TO KEEHI LAGOON, 1968 (AFTER PARSONS, 1968).

18, 1968, with a maximum count in the north-south runway of 1,100,000/ml on the earlier date.

The Ultramar studies showed dissolved oxygen concentrations increasing from 5.2 to 5.5 mg/l in the middle and the east side of the lagoon to 6.2 to 6.4 mg/l toward the west side. The temperature varies only slightly, from 28.0 to 28.2°C. Conductivities were essentially uniform over the area at 50.1 micromhos/cm, equivalent to a total dissolved solid concentration of 37.8°/₀₀; pH was essentially uniform at 8.18; phosphates were uniform at 0.025 mg/l; and nitrates, averaging 0.34, were slightly higher toward the middle of the lagoon than elsewhere. Organic nitrogen was 0.21 mg/l N.

Taken together, the results of long-term monitoring and short-term studies suggest that the waters in the Kalihi Channel and the eastern part of Keehi Lagoon do not meet the Class A standards with respect to upper decile coliform concentrations, although the waters in the western part are apparently satisfactory. The waters of the entering streams and the Sand Island channel do not meet the Class A standards with respect to any of the coliform standards, and in fact their fecal coliform concentrations exceed Class B standards.

A fish kill involving an estimated 1,000 fish, mainly of forage species, occurred in the Keehi Lagoon in May 1966. The source of the pollution was not determined. Additional kills have been reported from drainage canals opening to the shore between Keehi Lagoon and the entrance to Pearl Harbor, one in October 1960 and one in January 1964, the first involving both game and forage species and the second involving mainly game species. Both kills were described as "heavy." The source of the pollution in the second case was undetermined, and that in the first case was something other than domestic sewage, industrial wastes, food processing wastes, or poisons (FWPCA, 1961, 1965).

Honolulu Harbor

Honolulu Harbor (Fig. 22) on southern Oahu is the principal commercial port of the Hawaiian Islands. It is also the fifth most important source of nehu (bait fish) according to David Butchart of the State Department of Land and Natural Resources (Department of Health, 1966b). The harbor was originally a natural channel in the reef resulting from the fresh-water discharge of Nuuanu Stream. In numerous successive stages of dredging beginning in the mid-1800's, the size and depth of the harbor have been increased. It is now connected by deep water with Kapalama Basin, from which it was formerly separated by a shallow reef. Sand Island, southwest of the harbor, was, at successive stages, created by dredged fill, greatly enlarged and connected with the mainland west of Kapalama Basin, and again separated from the mainland by the present Kalihi ship channel. Other reef and lowland areas around the harbor have been filled, notably east of the harbor entrance. The harbor receives the flow not only of Nuuanu Stream, including that of its major tributary Pauoa Stream, but also considerable drainage from the Kapalama Canal. Nuuanu Stream originates in forest reserve lands in the Koolau crest area. Its valley is filled to the crest line with sediments and post-erosional lavas, from which some perched springs emerge. The stream flow is stabilized by three reservoirs, one of 1,630 acre/ft capacity. Pauoa Stream arises in a shorter

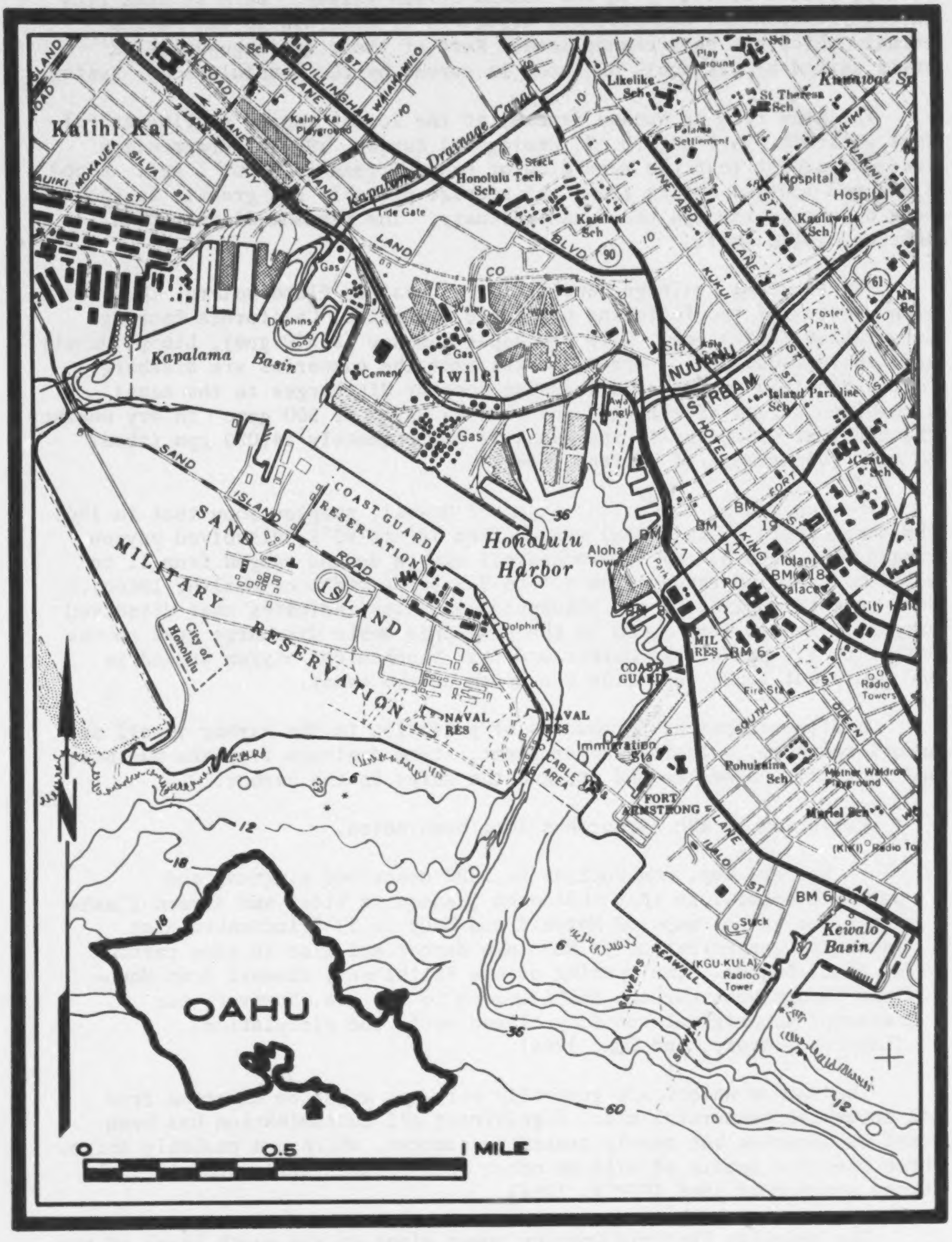


FIGURE 22. KAPALAMA BASIN, HONOLULU HARBOR, AND KEWALO BASIN.

valley, filled similarly to the Nuuanu Stream valley. Both streams flow through residential and business districts of Honolulu to the Nuuanu estuary which has been channelized. Part of their drainage areas is still served by cesspools but most is served by the Honolulu sewer system.

The mean flow of Nuuanu Stream, at the lowest gaging station at 631-foot altitude, is 5 mdg (U. S. Geological Survey, 1961). Fragmentary records suggest that the mean flow of Pauoa Stream is about 1 mgd. Flood flows and lowland spring flows and seepage probably add greatly to the mean discharge through the Nuuanu estuary. The minimum discharge is, however, quite small.

The Kapalama Drainage Canal carries, besides flood waters, the bland wastes of the following pineapple canneries, California Packing Corporation (3,000 gpm), Dole Pineapple Company (8,300 gpm), Libby, McNeil and Libby (2,000 gpm). Strong wastes from the canneries are discharged to the Honolulu sewer. Honolulu Gas Company discharges to the canal a combined stream of effluent and cooling water of 500 gpm. In dry weather the effluent discharge to the canal is approximately 14,000 gpm (about 20 mgd) (Department of Health, 1966b).

The Department of Health, State of Hawaii, samples show that in 1965 the temperature in the canal ranged from 78° to 95°F, dissolved oxygen ranged from 0 to 8.4 mg/1, biochemical oxygen demand ranged from 11 to 1,012 mg/1 and pH ranged from 4.4 to 9.2 (Department of Health, 1966b). More recent sampling by the pineapple companies indicates that dissolved oxygen increases from 3,000 in the pineapple waste discharge area to the Harbor to 5.5 ppm at the Harbor and that biochemical oxygen demand is 300 ppm about 1,500 feet from the mouth of the canal.

Additional potential sources of pollution to the harbor itself are an oil refinery, a thermal power plant, storm drainage from the business and industrial zones around it, and the ships in the harbor.

Pollution in the harbor has long been noted.

> Keller, Tay, and Collins in 1920 described stagnant and polluted conditions that indicated inadequate tidal and stream flushing. The isocol maps of Metcalf and Eddy in 1944 indicated high bacterial concentration in Honolulu Harbor and also in some parts of Keehi Lagoon. The opening of the Kalihi ship channel from Honolulu Harbor west through Keehi Lagoon to the sea, however, has restored an original but long closed route for circulation. (Laevastu, Avery, and Cox, 1964).

The harbor waters are generally oily, as might be expected from its intensive commercial use. Significant oil contamination has been noted on occasion but rarely traced to sources, which are probably ships. Three specific spills of oils or other dark liquids were noted in the second quarter of 1968 (FWPCA, 1968).

The Hawaiian Electric Company power plant on the north shore of the Harbor uses salt water from the Harbor for cooling and discharges the warm water back to the surface in the Harbor.

The median coliform content from six years of samples taken by the Department of Health at the Harbor entrance (Station 1, Table 11) is only 6 MPN/100 ml and the upper decile value only 700 MPN/100 ml. A recent 10-day intensive survey by the Department (Fig. 21 and Table 12) showed low concentrations of both total and fecal coliforms throughout the Harbor (median count less than 500/100 ml) except in the Sand Island channel and Kapalama Canal. In the Sand Island channel the medians of both total and fecal coliforms were greater than 125,000/100 ml, and the maxima were 8.7 x 10^6 for total and 6.9 x 10^6 for fecal coliforms/100 ml. In Kapalama Canal the total coliforms showed a median of over 20 x 10^6 and a maximum of 22 x 10^6/100 ml, and fecal coliforms a median of 14 x 10^6 and a maximum of 227 x 10^6/100 ml.

The Harbor has been designated as a Class B coastal water, but even for this class the fecal coliform content in the Kapalama Canal and Sand Island channel very greatly exceed the standards.

Three moderate to heavy fish-kills have occurred in the Kapalama Canal. The first, occurring in May 1963, and third, in September 1966, which involved mainly forage species, were attributed to "food and kindred products." For the second which occurred in July 1965 and involved in estimated 100,000 fish, the cause was undetermined (FWPCA, 1964, 1966, 1967).

Ala Wai Canal and Yacht Basin and Kewalo Basin

The coastal area from a mile east of Honolulu to the slopes of Diamond Head, except for the beach ridge along the shore, was originally swampy (Fig. 18). The swamp was fed by the perennial streams of Manoa and Palolo, which had their common outlet in Waikiki; by freshet flows from other, intermittent streams; and by springs emerging from the corals interbedded with the other coastal plain sediments. Taro patches, rice paddies, duck ponds, and fish ponds were common. The Ala Wai Canal was dredged in the 1920's mainly as a health measure to reduce the mosquito population. The material dredged was used to fill in lowland areas, the streams were intercepted by the canal and channelized upstream, and ground-water levels were lowered to dry the entire area (Figs. 19 and 23).

The canal was dredged to the shore at the Ala Wai Yacht Harbor, but was not originally continued across the reef there. Instead, the dredging was continued westward along the shore to Kewalo Basin (Fig. 22), which was dredged at about the same time, and thence across the reef to the open sea. In the 1950's the present Ala Wai channel was dredged to the sea, and the original channel along the shore was filled at both the Ala Wai and Kewalo ends (Fig. 23).

Gaging stations at the lowest elevations on the two tributaries of Manoa Stream and two tributaries of Palolo Stream the mean flows total 8.2 mgd. Mean discharge of the canal, however, must be at least twice this because of flood flows from the lower stream valleys, ungaged intermittent tributaries, and storm sewers in the coastal plain. The total minimum gaged is 0.6 mgd but even minimum discharge of the canal must be

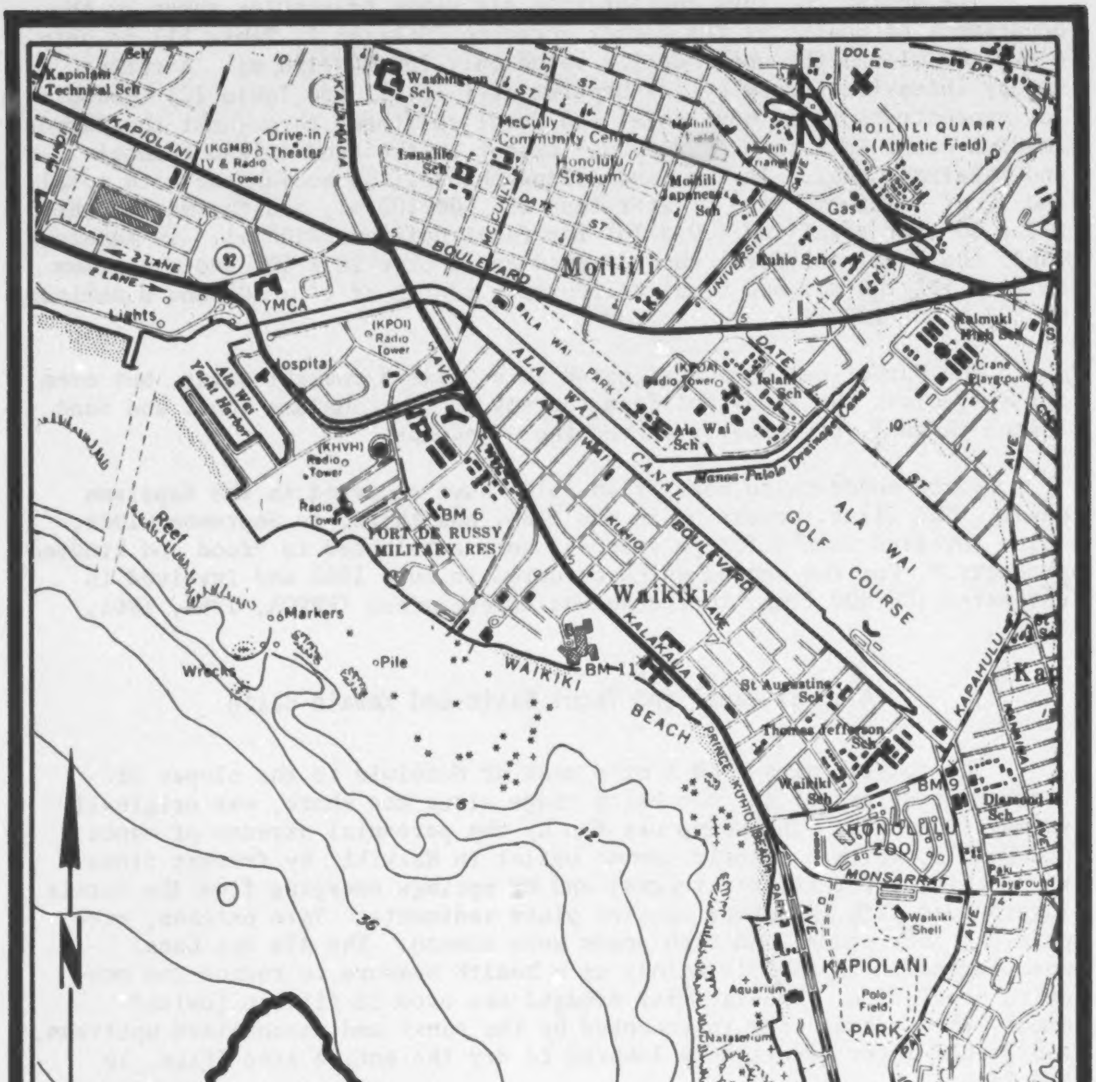


FIGURE 23. ALA WAI CANAL AND YACHT BASIN.

a few mgd because of spring flow and seepage from the coastal plain.

Although the heads of Manoa and Palolo Valleys and the upper parts of the ridges in the tributary areas are in forest reserve, most of the drainage area tributary to the canal is in urban residential or business use.

The yacht harbor has been designated a Class B coastal water. From its tidal behavior and the lack of specific designation to the contrary, the canal must be included in Class A. Analyses by the Department of Health from 1959 or 1961 to 1968 or 1969 (Table 11) indicate the water of the canal is far from meeting the coliform standard for Class A water and, in fact, that the harbor water is of much better quality, probably because of dilution by sea water of the bacterial concentrations introduced from the canal. The median coliform concentrations are 2,400 MPN/100 ml in the harbor. Upper decile values are 70,000, 7,000, and 7,000 MPN/100 ml for the McCully Bridge, Ala Moana Bridge, and Harbor, respectively.

The water discharged by the canal is muddy during flood periods, and numerous complaints are made of floating trash from the canal accumulating in the Yacht Basin. Oil is reported to pollute the basin at times during Kona (south wind) weather. Heavy oil contamination occurring in June 1969 has been attributed tentatively to a ship cleaning its oil tanks offshore (Honolulu Star Bulletin, June 16, 1969).

The dermatitis known locally as "Pearl Harbor itch" (Arnold and Bonnet, 1950) was reported in 1948-49 from the Ala Wai canal.

According to Garth Murphy (personal communication), the mullet that were once common in the upper reaches of the canal have disappeared, probably as the result of the formation of a silt sill at the entrance to the canal of the Manoa Stream channel and the stagnation and anaerobic conditions that have resulted at the bottom toward the canal head.

Kewalo Basin (Fig. 22), which has been designated a Class B coastal water, may once have received some pollution from the tuna cannery located there. However, the cannery wastes are now discharged into the municipal sewer system (Chun, Department of Health, 1966b). Department of Health samples for the period 1959-1968 (Table 11) show a meidan coliform concentration of 2,400 MPN/100 ml and an upper decile value of 7,000 MPN/100 ml.

Kuapa Pond

Kuapa Pond in southeastern Oahu (Fig. 24) was until a few years ago a large mullet pond occupying what had once been a bay lying between southeasterly ridges of the Koolau Range and Koko Head, a youthful tuff cone. Until the 1930's the pond was separated from the ocean by only a narrow beach ridge. The beach strip was then widened when a highway was built along it. The pond has now been reduced by dredging to a series of channels separated by points and islands, which are rapidly being developed as a residential district, and the entrance has been enlarged for small boat navigation and drainage. Both the natural lands and the filled lands bordering the pond, as well as lands extending up four short valleys

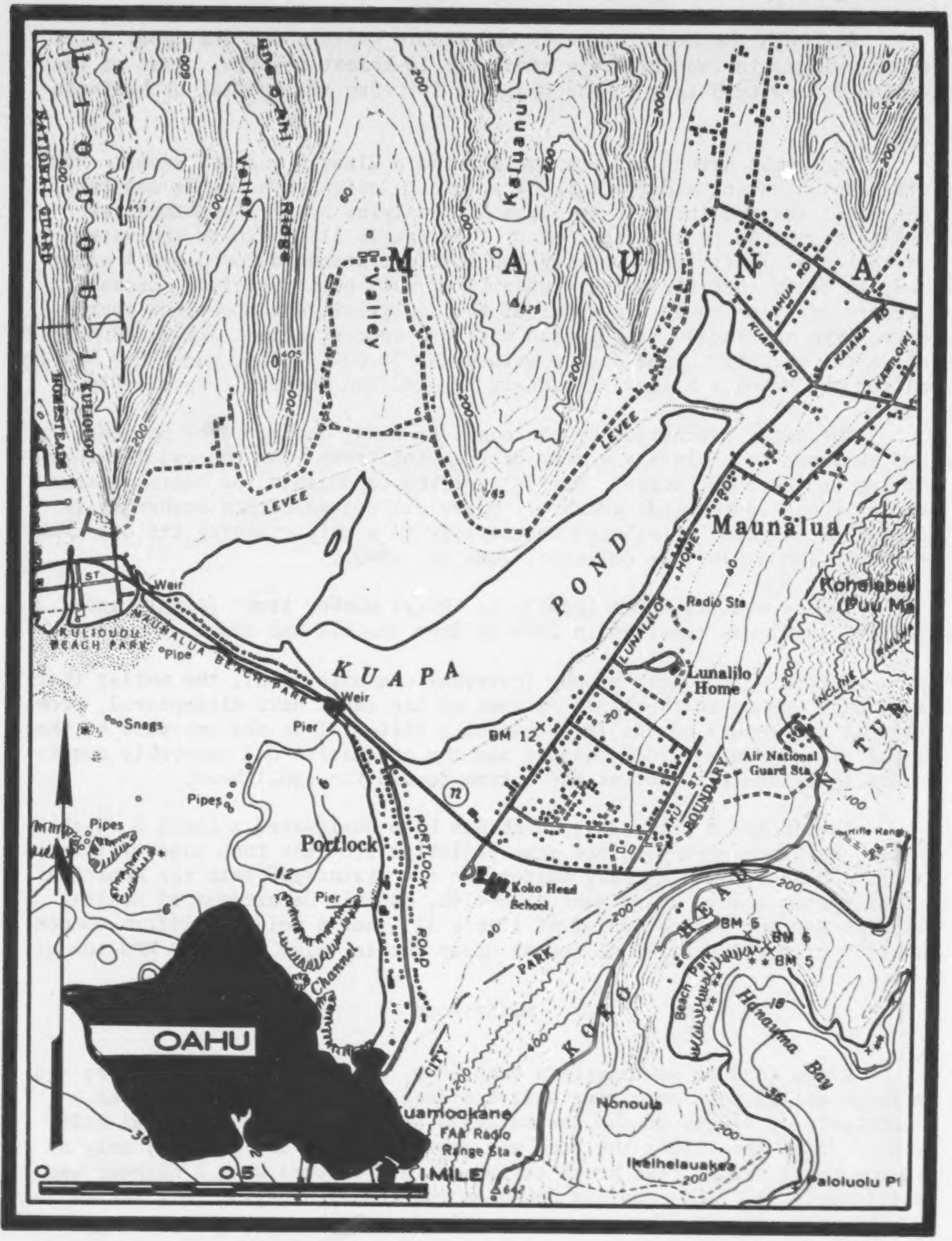


FIGURE 24. KUAPA POND

in the Koolau Range tributary to the pond, are rapidly filling with residences. There were once piggeries in the two westernmost tributary valleys and the lands between the pond and Koko Head Crater were once in truck farms, but these are now displaced.

The fresh water supply of the pond area is derived from rainfall in the area, freshet flows of the short intermittent tributary streams, and probably some brackish basal spring slow.

The major present pollutant is silt from the derdging operations and adjacent land development.

Waimanalo Stream

Waimanalo Stream, near the southwest end of the northeastern coast of Oahu (Fig. 25), drains a former swamp on the northwest side of Waimanalo Valley fed by intermittent streams probably supplemented by low-level springs. Its mouth, now channelized, is tidal. The headwaters of the stream are on part of the pali (cliff) that has been eroded into much of the northeast part of the Koolau Range. Downstream the valley crosses deeply weathered bedrock with numerous dikes and then a coastal plain. The drainage area tributary to the stream is mainly rural including truck crop area, orchards, and cattle and horse pastures. The headwaters are in steep bedrock forest reserve and the shore area is a military base.

Takasaki, *et al.*, (1969) estimate the mean flow of Waimanalo Stream as 0.7 mgd. The water in the estuarine portion becomes increasingly saline toward its mouth, the chloride content reaching 14.5 parts per thousand at the lowest bridge. No information on pollution of the stream has been found.

Although Waimanalo Bay has been designated a Class AA coastal water, Waimanalo Stream is probably not meant to be included. From its location the stream estuary should be in Class A coastal waters. No information appears to be available to indicate whether its quality meets the standards for the class.

Kaelepulu Stream and Kawainui Canal

Kaelepulu Stream (Fig. 26), entering the ocean in the southeast part of Kailua, formerly drained the entire Kailua area including, not only the part of the coastal plain in the immediate vicinity and Kaelepulu Valley inland, but also the northwestern part of the coastal plain, in which is Kawainui Swamp, and Maunawili Valley.

Kaelepulu Valley is cut into dike-intruded, deeply altered, and weathered lavas of the Koolau volcano. Part of the coastal plain seaward of the valley was occupied by the Kaelepuli Swamp which has now been developed to make a series of channels separated by filled land known as Enchanted Lake. The former swamp drained, as the present lake does, through the estuarine part of Kaelepulu Stream.

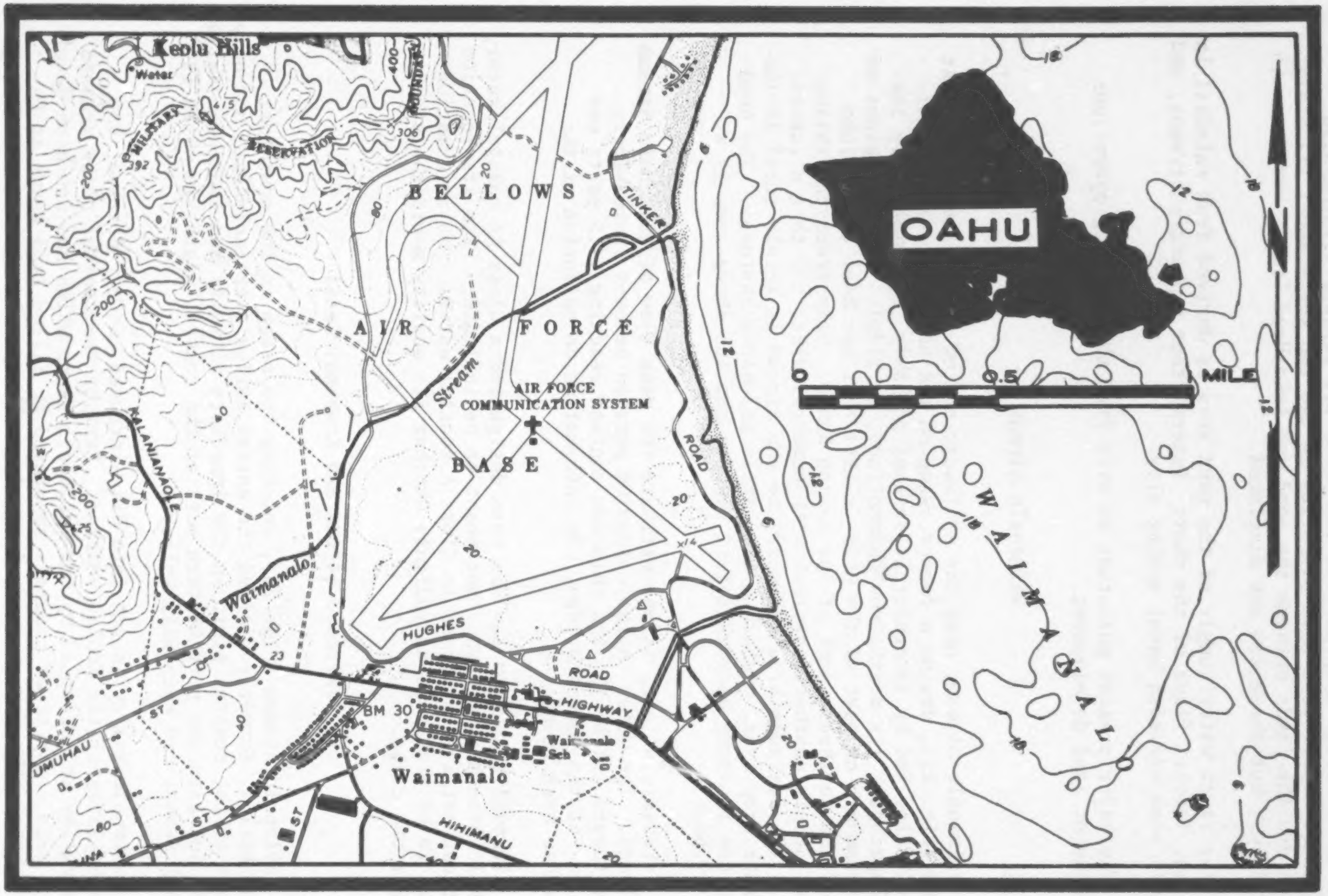


FIGURE 25. WAIMANALO STREAM.

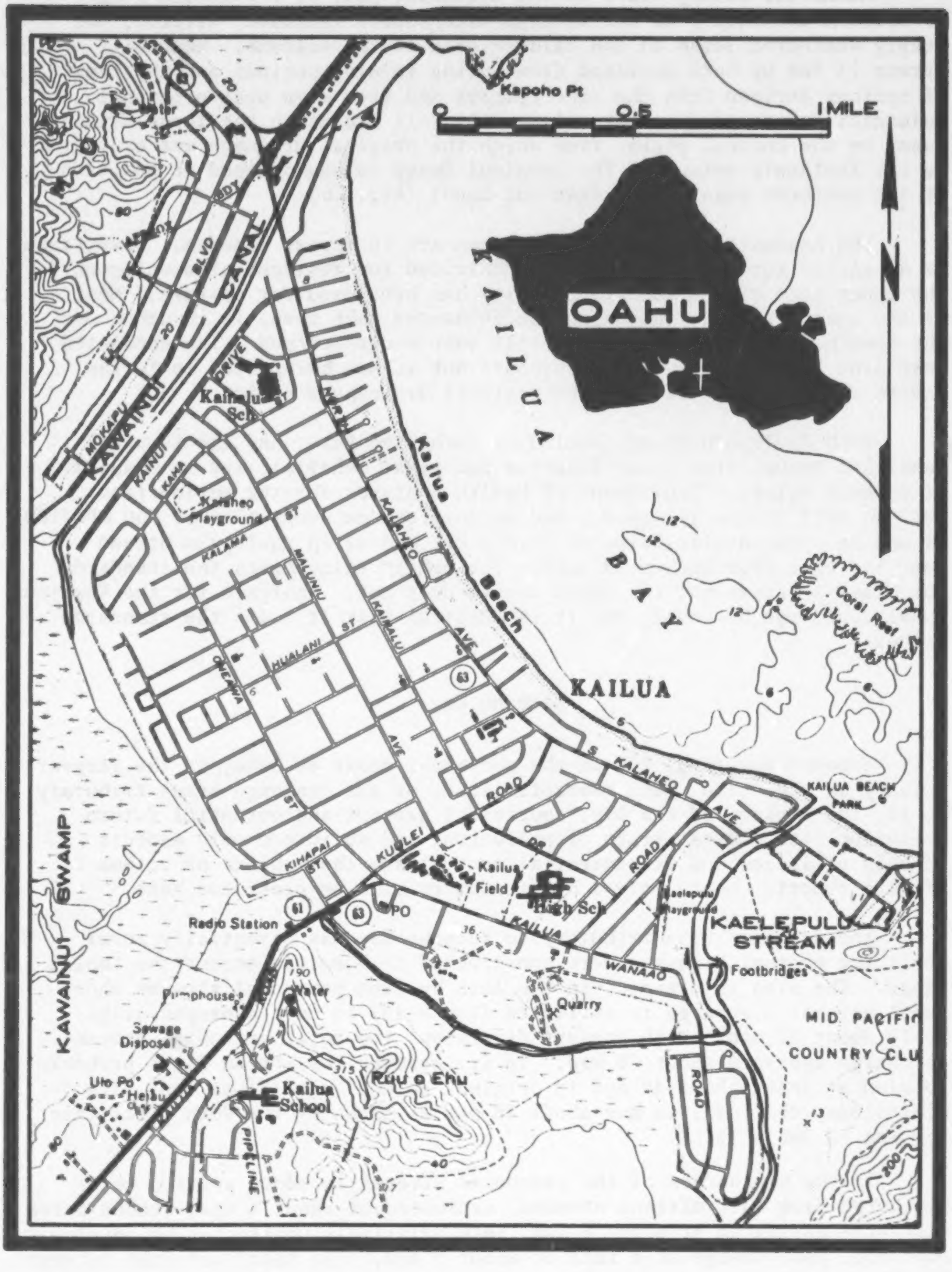


FIGURE 26. KAELEPULU STREAM AND KAWAINUI CANAL.

Maunawili Valley heads on the northeast pali of the Koolau Range. Downstream the valley is cut through extensively intruded, altered, and deeply weathered lavas in the caldera area of the volcano. Maunawili Stream is fed by both overland flow during raining periods and the flow of springs derived from the dike complex and from some post-erosional volcanics interbedded in the valley fill. It drains to the large Kawainui Swamp on the coastal plain, from which the original drainage was eastward to the Kaelepulu estuary. The Kawainui Swamp is now drained in addition at its northern edge by the Kawainui Canal (Fig. 26).

The headwaters of Maunawili Stream are in forest reserve. Downstream is an agricultural area now being subdivided for residential development. The upper part of the Kaelepulu Valley has been used for pasture. Most of the coastal plain, including the Enchanted Lake area, is in urban use. The Kawainui Swamp, however, is still mainly undeveloped. The Enchanted Lake area has been served by cesspools but is now being tied in to the sewers recently installed in the regional drainage district.

Both Kaelepulu Strea, including Enchanted Lake, and the Kawainui Canal and Swamp, from their location and tidal behavior, are in Class A of coastal waters. Department of Health analyses for the period from 1957 to 1969 (Table 11) show a median coliform concentration of 700 MPN/100 ml and an upper decile value of 24,000 MPN 100 ml in Kaelepulu Stream near its exit from Enchanted Lake. The median value meets the standard for Class A waters but the upper decile does not. Analyses for the Kawainui Canal could not be found, but it is doubtful that it meets the standards either.

Kaneohe Bay

Kaneohe Bay (Fig. 27) on the northeast coast of Oahu, is the largest estuary in the state. The characteristics of the drainage areas tributary to it, the ecology of the Bay, sources of present and potential future pollution, its present state of pollution, and socio-economic aspects of this pollution and its potential control are the subject of volume II of this report. Hence only a brief summary will be presented here.

The drainage area tributary to Kaneohe Bay was essentially rural until the present highways were constructed to Honolulu across the Koolau Range. The area is drained, in the main by nine perennial streams whose total natural discharge is estimated (Table 13) to have averaged originally about 82 mgd. With present diversions the total perennial stream discharge averages about 48 mgd. In dry weather the stream flows probably totaled at least about 49 mgd in original natural conditions and, with diversions, the total is now about 18 mgd as shown by the 90th percentile figures in Table 13.

To the discharges of the perennial streams is added surface water discharge from intermittent streams, estimated at about 6 mgd, ground-water discharge estimated at about 6 mgd, both relatively unaffected by development and, now, sewage at a rate of about 3 mgd. The total original natural fresh-water discharge to the Bay is thus estimated at 97 mgd and the present discharge at 60 mgd.

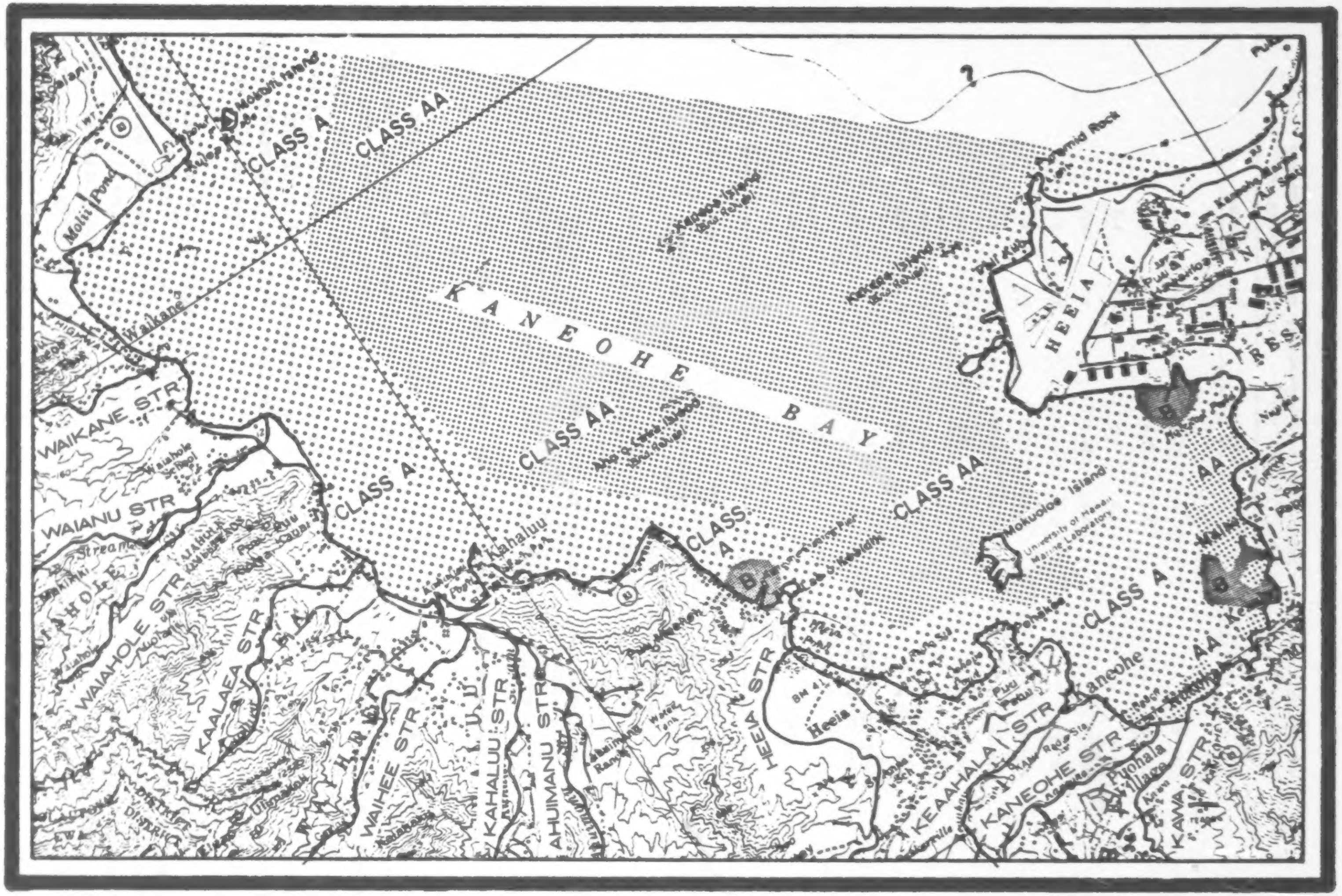


FIGURE 27. WATER QUALITY CLASSIFICATION MAP OF KANEOHE BAY.

TABLE 13. PERENNIAL STREAM DISCHARGES TO KANEOHE BAY.

INVENTORIED STREAM	NATURAL DISCHARGES, MGD A)		PRESENT DISCHARGES, MGD B)	
	Q_{90}	Q_{MEAN}	Q_{90}	Q_{MEAN}
KAWA	0.2	1.0	0.2	1.0
KANEOHE	7.2	12.6	5.5	10.9
KEAAHALA	2.2	3.4	2.2	3.4
HEEIA	2.8	5.5	0.6	3.3
KAHALUU	10.2	18.7	2.4	10.9
KAALAEA	0.6	2.4	0.6	2.4
WAIAHOLE	17.0±	23.8±	4.4	8.1
WAIKANE	6.1±	10.3±	1.4	4.2
HAKIPU	0.4	1.1	0.4	1.1
SUB TOTALS	46.7	78.8	17.7	45.3
ESTIMATED CONTRIBUTIONS BELOW INVENTORIED AREA C)		2 TO 4		2 TO 4
TOTALS (ROUNDED)		81 TO 83		47 TO 49

A) INDIVIDUAL INVENTORIED DISCHARGES ARE AS ESTIMATED BY TAKASAKI, ET AL., (1969) WITH THE FOLLOWING EXCEPTIONS:

I. FOR KANEOHE THE ESTIMATE HAS BEEN INCREASED BY THE 1.3 MGD NORMAL DIVERSIONS FROM THE KUOU WELLS AND LULUKU TUNNEL WHICH BEGAN BEFORE THE PERIOD OF STREAM GAGING.

II. THE SUMS FOR WAIAHOLE AND WAIKANE ARE AS GIVEN BY TAKASAKI, ET AL., AND THE APPROXIMATE DISTRIBUTION IS BASED ON FRAGMENTARY RECORDS SUMMARIZED BY THE TERRITORIAL PLANNING BOARD (1939).

B) FOR KANEOHE, HEEIA, AND KAHALUU, PRESENT INVENTORIED DISCHARGES ARE NATURAL DISCHARGES REDUCED BY 1968 DIKE-TUNNEL AND MAJOR WELL WITHDRAWALS IN THEIR RESPECTIVE VALLEYS. FOR WAIAHOLE AND WAIKANE PRESENT DISCHARGES ARE AS ESTIMATED BY TAKASAKI, ET AL. FOR OTHER STREAMS NATURAL DISCHARGES ARE UNREDUCED.

C) CONTRIBUTIONS BELOW INVENTORIED AREAS ARE ESTIMATED AS EXPLAINED IN TEXT.

The Bay itself is in detail a coastal-plain estuary occupying a drowned stream-valley system eroded in sediments occupying older, deeper-submerged and filled, coalescent valleys cut in bedrock. Across the mouth of the Bay is a coral barrier reef. Connecting the Bay with the ocean across the reef is a shallow eastern channel and a western channel dredged to 30 to 35 feet. There are also a fringing coral reef and isolated reefs in the Bay, all at shallow depths. Between the reefs, the Bay depth varies generally from 30 to 45 feet with a maximum of 62 feet.

The major currents of the Bay are tidal in nature. On a rising tide water enters through a shallow eastern channel and a deeper western channel and over the whole barrier reef. On a falling tide the discharge is mainly through the channels, the flow over the reef ordinarily being still shoreward, especially in trade-wind weather. In the southeast part of the bay there is a semi-persistent counter-clockwise eddy.

Precipitation and evapotranspiration over the Bay are approximately equal, hence the net transport from the Bay is essentially equal to the stream, ground water, and sewage inflow. The daily exchange transport for the Bay is very much larger, about 4,840 mgd or 26 percent of the Bay volume. The daily exchange transport of the southwest part of the Bay is, however, only about 46 mgd, or 0.4 percent of the volume of that part of the Bay.

Ecologically, the Bay may be divided into three regions: a northern region, which has the greatest fresh-water discharge and salt-water exchange; a central region in which the circulation is more restricted by the barrier reef; and a southern region, which has comparatively poor circulation. Within these regions are three zones: an inshore zone, consisting of the fringing reef, with superimposed mud, silt, sand, and rubble deposits; a middle zone, characterized by the mud-bottomed channels and the coral patch reefs of the bay; and, in the central and northern regime, an outer zone consisting of the barrier reef. In the northern region of the bay are many elements of the oceanic biota, in the central region of the bay, some inshore and some oceanic forms, and in the southern region, more restricted flora and fauna with larger numbers and fewer species.

The Bay is used extensively for recreation and as a fishery for the bait fish, nehu. In addition, it is a fishery for game fish, and other organisms such as octopus and introduced clams.

Under the Water Quality Standards set by the Public Health Regulations of the State of Hawaii, the waters of the entire central part of the Bay are designated Class AA, the highest quality of coastal waters. The margins of the Bay are designated as Class A except for three small areas in the vicinity of the small boat harbors which are designated Class B. The locations of the several classes are shown in Figure 27.

The principal sources of pollution of the bay are the perennial streams, intermittent streams, and two sewage outfalls, one serving the town of Kaneohe and the other the Kaneohe Marine Corps Air Station in Mokapu peninsula, east of the Bay. The municipal outfall carries discharge from a secondary sewage treatment plant and the military outfall discharge from a primary treatment plant. A small amount of raw sewage is discharged from the marine laboratory on Mokuoloe Island.

During the study in 1968-69, median and maximum total coliform concentrations, and mean and 90th percentile fecal coliform concentrations were found generally to exceed the Class A tolerance limits in most of the streams draining to the Bay. The fecal coliform concentrations, in fact, exceeded the tolerance limits set for Class B waters. Although the sample points were in some cases upstream from the estuarine portions of the streams, there is no reason to believe that the bacterial concentrations would be materially lower in upper reaches of the estuarine portions.

Fecal coliform concentrations were also found generally to exceed the tolerances set for Class A, and even Class B waters at the surface of the Bay in the vicinity of the outfall from the Kaneohe Marine Corps Air Station sewage treatment plant during the first half year of the study, and on two occasions exceeded the maximum tolerance for Class A and B waters over the outfall from the municipal sewage treatment plant. In most of the Bay, however, the waters met Class AA standards so far as bacterial concentrations were concerned.

Total nitrogen concentrations generally exceeded the tolerances set for both Class A and Class B waters in all the streams sampled. The minumum phosphorus concentrations in the streams fell within the established tolerances, but the maxima exceeded the tolerances in all streams sampled. In the bay the phosphorus concentrations were found to decrease very rapidly away from the points of discharge and with respect to phosphorus the Bay waters generally fell with Class AA tolerances. Nitrogen concentrations, however, were found to exceed the Class AA tolerance limits not only throughout the Bay but offshore as well.

During dry-weather periods very little sediment is discharged to the Bay, but during floods both the perennial and intermittent streams discharge large amounts of silt and the waters of the way become noticeably turbid. One stream, Kamooalii, discharged an estimated 9,470 tons of sediment to the Bay in a single 24-hour storm period in February 1969.

It is clear that the estuarine waters of the Bay and tributary stream mouths in certain respects to meet the standards set for the water quality classes to which they have been assigned. So far as the sewage effluent discharges are concerned, the violation of the standards would be eliminated, with the exception of nitrogen tolerance level, by the establishment of zones of mixing as permitted under the Public Health Regulations. The real consequences of the violations of the standards, possible means of treatment, and economic aspects are discussed in volume II of this report.

Kahana Stream and Bay

Kahana Bay (Fig. 28) near the middle of the northeast coast of Oahu, is the drowned lower portion of a valley eroded in the lava-flow flank of the Koolau Range. Kahana Stream, entering the bay across the sedimentary fill of the upper part of the unchanged valley, is tidal for about half a mile. The upper end of the valley is cut into the dike complex in the high rainfall part of the Koolau Range and the dry weather flow of the stream is supplied by dike springs.

According to Takasaki, *et al.*, (1969) the long-term mean discharge of Kahana Stream to the Bay under present conditions is about 29.5 mgd and the discharge is in excess of 11.2 mgd 90 percent of the time. An average of 7.2 mgd is, however, diverted inland and exported from the valley by the Waiahole ditch system, so the original natural mean flow must have been nearly 37 mgd and the ninetieth percentile flow about 18 mgd.

The beach at the head of Kahana Bay is composed mostly of carbonate sand (Moberly and Chamberlain, 1964), and the bay has a sand bottom except for coral reefs flanking both sides. The channel between these reefs continues across the full width of the reef offshore and beyond, as a submarine valley. Because of the magnitude of the dry-weather flow of the stream the river mouth never becomes greatly constricted by sand bars.

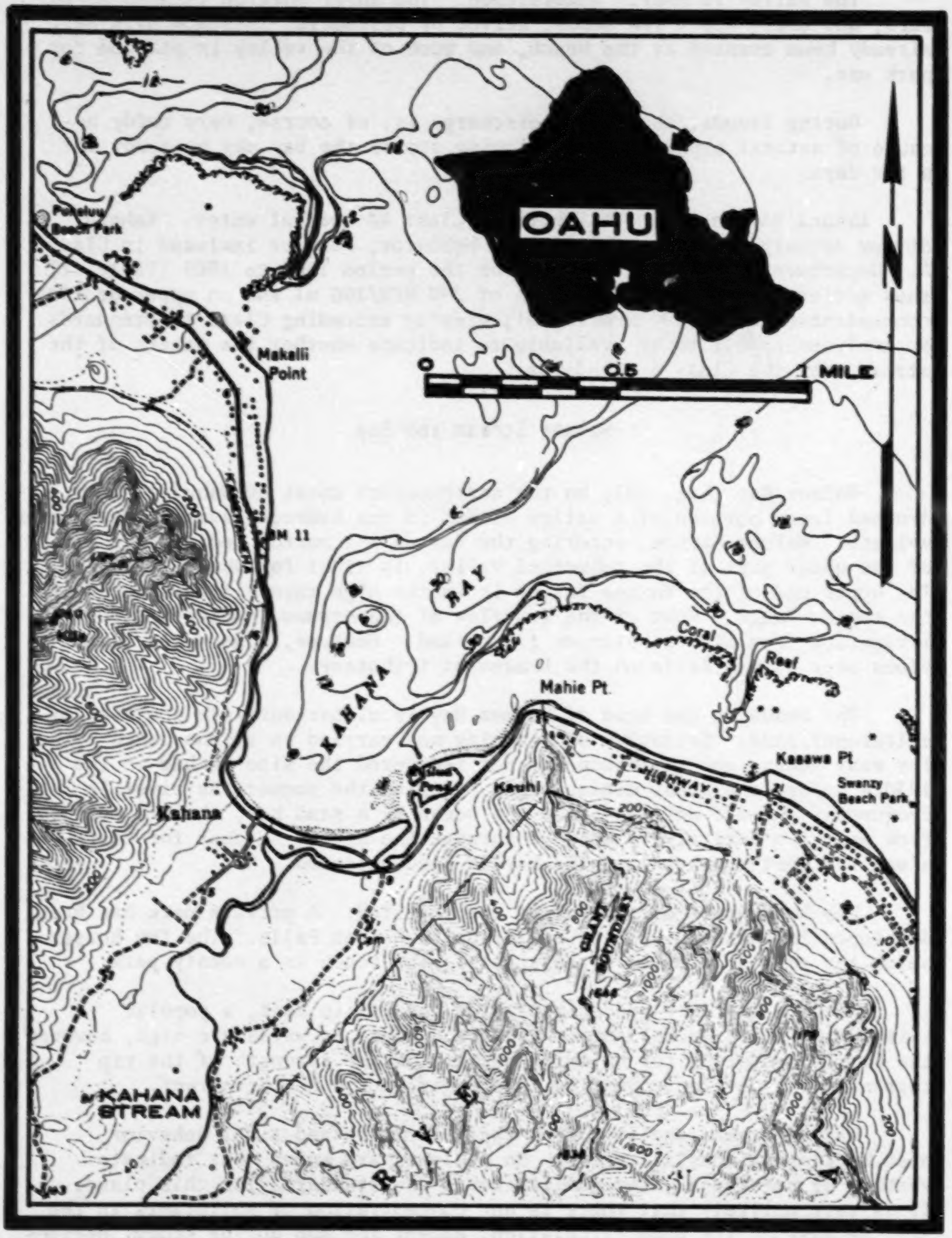


FIGURE 28. KAHANA STREAM AND BAY.

The valley is nearly undeveloped. The lower portion is used as pasture, and there are a few homes, served by cesspools. A state park has already been created at the beach, and much of the valley is planned for park use.

During floods, the stream discharge is, of course, very muddy because of natural erosion, and following storms the Bay may be muddy for a few days.

Kahana Bay has been designated a Class AA coastal water. Kahana Stream estuary, because of its tidal behavior, must be included in Class A. Department of Health analyses for the period 1965 to 1969 (Table 11) show median coliform concentration of 240 MPN/100 ml and an upper decile concentration of 24,000 MPN/100 ml, greatly exceeding Class AA standards. No analyses appear to be available to indicate whether the waters of the stream meet the Class A standards.

Waimea Stream and Bay

Waimea Bay (Fig. 29), on the northwestern coast of Oahu, is the drowned lower portion of a valley eroded in the bedrock lavas of the Koolau volcano. Waimea Stream, entering the Bay on the narrow sedimentary fill of the upper part of the submerged valley, is tidal for about 2,000 feet. The upper end of the Waimea Valley is in the high rainfall crest area of the Koolau Range. Most of the low flow of the stream is diverted for irrigation from its tributaries far inland. However, some water always flows over Waimea Falls on the Kamananui tributary.

The beach at the head of Waimea Bay is almost entirely composed of calcareous sand. Extensive sand mining was carried on at the beach for many years, and the beach has not recovered the size it had in the 1930's before the heavy mining began. During the summer the river is frequently cut off entirely from the ocean by a sand bar, the dry weather flow entering entirely by seepage through the beach. Except for reefs along the northern headland the bay is sand bottomed.

The headwaters of the Waimea are forested. A private park has been developed in Kamananui Valley as far up as Waimea Falls. The few houses below the park are served by cesspools. The beach is a county park.

The park has very good circulation and is, in fact, a popular swimming place in normal summer weather. When the waves are high, however, the bay is dangerous for swimming because of the strength of the rip currents that develop. Surfing is popular on the northern reef.

Waimea Stream and Bay, from their location and tidal behavior, must be Class A coastal waters. No analyses are known that indicate whether or not their water quality meets the standards for this class. It is very unlikely that there is any concentration of pollutants in the Bay, because of its good circulation, except for mud during stormy periods when the river introduces muddy water.

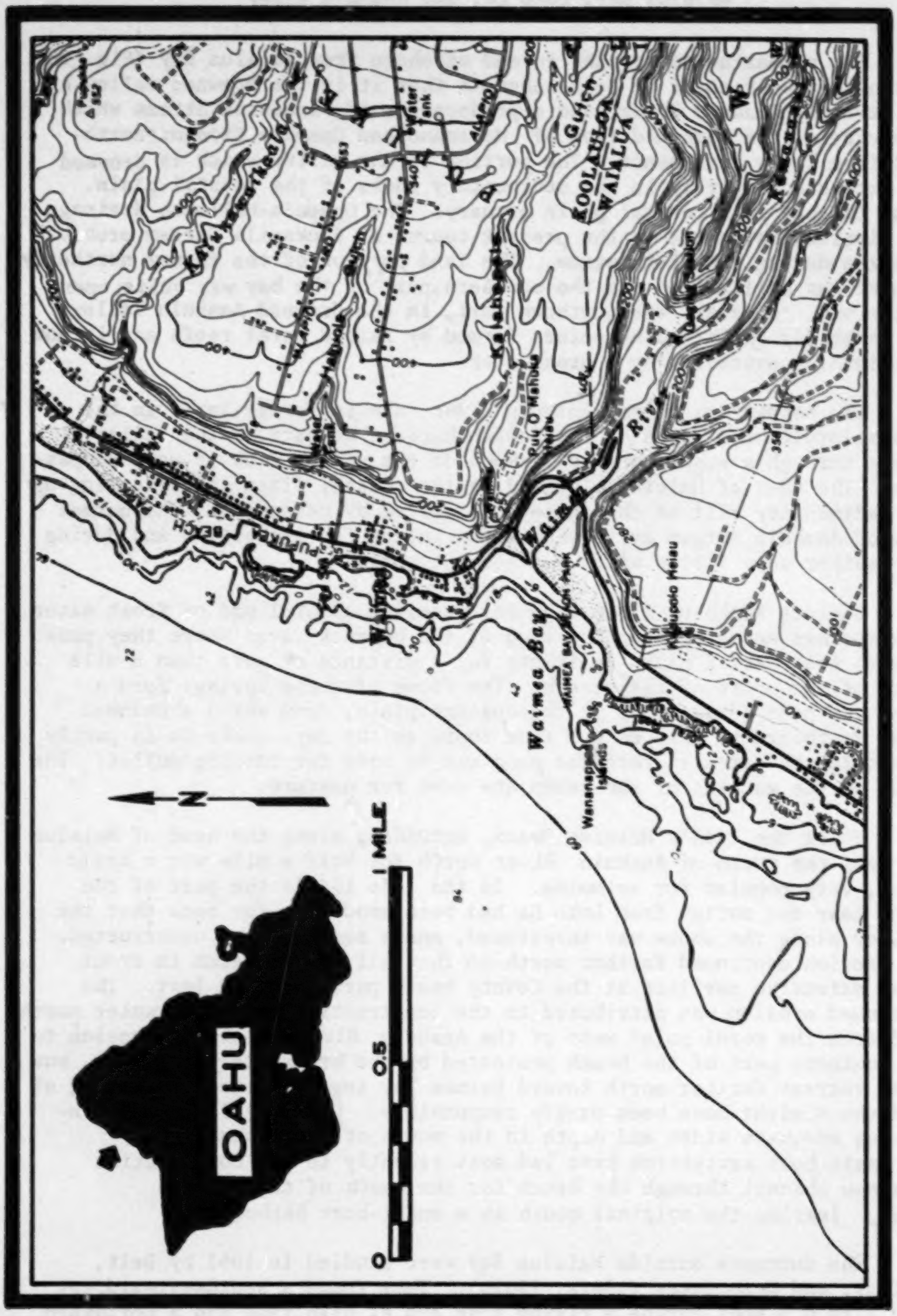


FIGURE 29. WAIMEA STREAM AND BAY.

Waialua Bay, Loko Ea, and Anahulu River

The submarine topography in and offshore from Waialua Bay (Fig. 30) on the northwest coast of Oahu suggests that it is the drowned valley of two streams, Anahulu River and a predecessor of Paukauila Stream which once carried the combined flow of Helemano and Opaeula Streams northward from their confluence. The portion of the valley which is drowned was excavated entirely in the sedimentary rocks of the coastal plain. Hence the bay is a coastal plain estuary. The Opaeula-Helemano drainage was diverted southwest to the present course of Paukauila Stream probably sometime during the Pleistocene. The land portion of the former northerly channel was obliterated and the southern part of the bay was quite open to the sea. However, the northern part, in the drowned Anahulu Valley, was partially sheltered by points formed by raised coral reefs and is now additionally protected by a breakwater.

The headwaters of the Anahulu River are in forest lands in the high-rainfall crest area of the Koolau Range. Downstream the valley passes through a sugarcane area. Much of the valley flow is used as pasture. The town of Haleiwa, located on the coastal plain and extending up the sedimentary fill of the valley, is served by cesspools. The normal flow of Anahulu Stream are diverted far inland for irrigation and during dry weather very little water reaches the coast.

Besides Anahulu River, the Bay receives about 1 mgd of fresh water from springs emerging from the edge of the bedrock lavas where they pass beneath the coastal plain sediments for a distance of more than a mile north of the mouth of the stream. The flows of these springs form a swamp and pond (Ukoa Pond) on the coastal plain, from which a channel leads southward to Loko Ea and from there to the Bay. Loko Ea is partly controlled by gates so that the pond can be used for raising mullet. The lands on the margins of the swamp are used for pasture.

Until the 1940's Haleiwa Beach, extending along the head of Waialua Bay from the mouth of Anahulu River north for half a mile was a broad beach, very popular for swimming. In the late 1940's the part of the beach near the outlet from Loko Ea had been eroded so far back that the highway along the shore was threatened, and a sea wall was constructed. The erosion continued farther north so that all of the beach in front of an extensive pavilion at the County beach part had been lost. The continued erosion was attributed to the construction of a breakwater northward from the coral point west of the Anahulu River mouth. Accretion to the southern part of the beach protected by the breakwater did occur, but beach retreat farther north toward Waimea Bay suggests that the mining of sand there might have been partly responsible. Difficulties with maintaining adequate width and depth in the mouth of the Anahulu River for small-boat navigation have led most recently to the construction of a new channel through the beach for the mouth of the Anahulu River, leaving the original mouth as a small-boat harbor.

The currents outside Waialua Bay were studied in 1961 by Belt, Collins, and Associates (1962a, 1962b). They found a southwestward set of 0.2 to 0.3 knot during a rising tide and at high tide and a northward set of 0.1 to 0.2 knot at low tides.

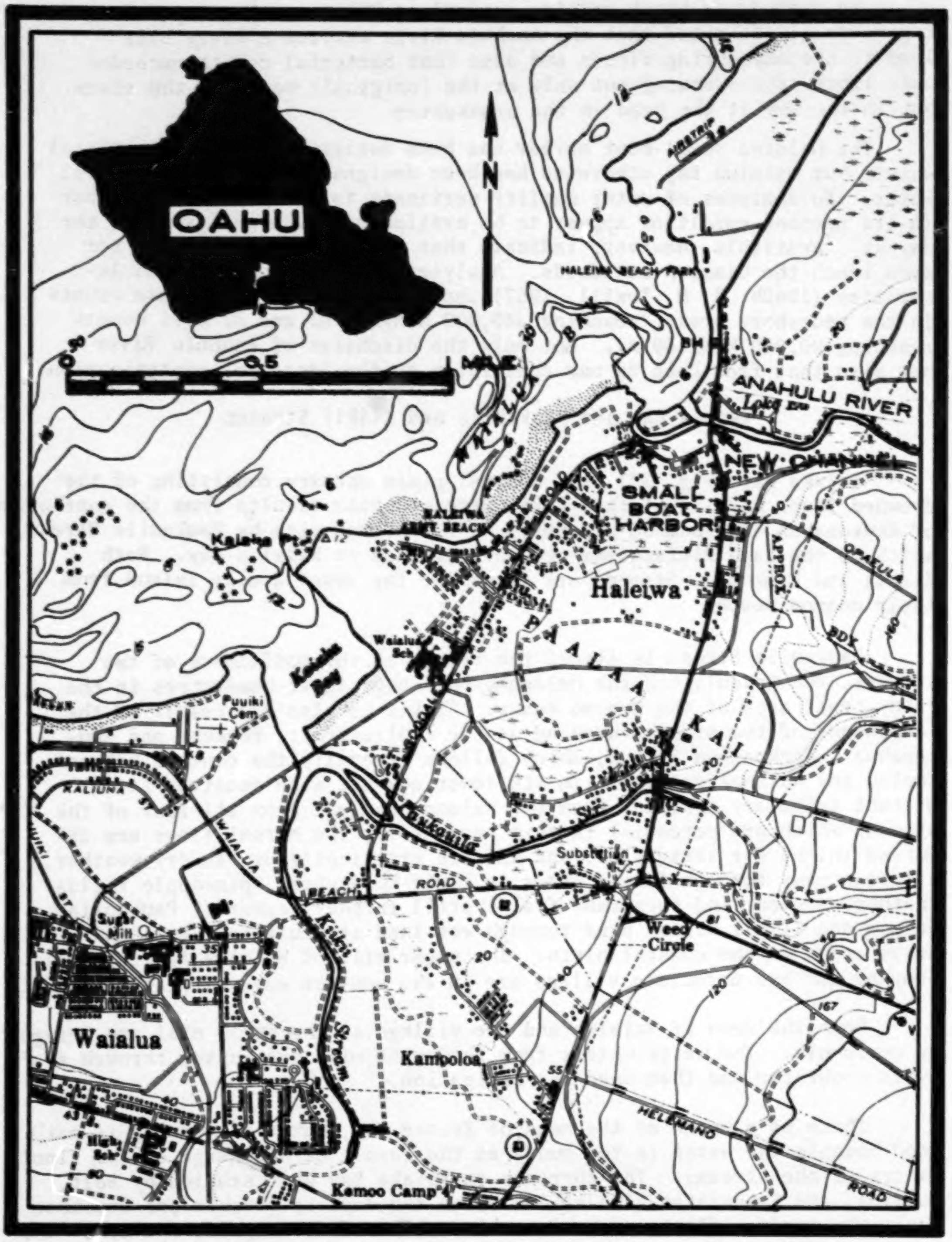


FIGURE 30. WAIALUA AND KAIAKA BAYS, LOKO EA, ANAHULU RIVER, AND PAUKAUILA AND KIIKII STREAMS.

In a study of beach erosion control at Haleiwa, the Corps of Engineers (1965) noted that the Anahulu River carries a heavy silt load to the bay during floods and also that bacterial counts exceeded safe limits for swimming not only at the (original) mouth of the river but in the bay at the bend in the breakwater.

The Haleiwa small-boat harbor has been designated a Class B coastal water, but Waialua Bay otherwise has been designated a Class AA coastal water. No analyses of water quality pertinent to the small-boat harbor in its present condition appear to be available. Such analyses for the Bay as available, however, indicate that the water quality does not even reach the Class A standards. Analyses by Belt, Collins, and Associates (1962b; R. M. Towill, 1967) show generally high coliform counts in the nearshore areas, reaching 240,000 MPN/100 ml and *E. coli* counts reaching 90,000 MPN/100 ml. Not only the discharge of Anahulu River but also that from Loko Ea may contribute to the bacterial contamination.

Kaiaka Bay and Paukauila and Kiikii Streams

Kaiaka Bay (Fig. 30) is a coastal plain estuary consisting of the drowned lower portion of the Kiikii Stream, which results from the confluence of Kaukonahua and Poamoho Streams. It is entered also by Paukauila Stream, which in the late Pleistocene probably drained to Waialua Bay. Both Kiikii and Paukauila Streams are estuarine for about a mile inland from their common mouth.

Paukauila Stream is itself the result of the confluence of two streams, the Opaeula and the Helemano-both have their headwaters in the rainy crest area of the Koolau Range. Kiikii is also the result of the confluence of two streams heading at the Koolau crest, Poamoho and Kaukonahua. Kaukonahua Stream, which follows generally the contact between Koolau and Waianae volcanoes in its lower course, also receives intermittent tributary drainage from the Waianae Range. From all four of the streams which are perennial in this headwaters, the normal flows are diverted inland for irrigation, and all are practically dry in dry weather. All four pass through forest lands in their headwaters, pineapple fields farther seaward, and sugarcane fields still farther seaward. Paukauila Stream and Kiikii Stream pass through wet-land agricultural areas and urban areas on the coastal plain. The sugar mill of Waialua Agricultural Company and its associate village are in the western edge of Kiikii Valley.

Both the town of Waialua and the village at the sugar mill are served by cesspools. The waste waters from the sugar mill are passed through a hydro-separator and then used for irrigation.

There is a beach at the head of Kaiaka Bay, but the swimming is not good because the water is too muddy as the result of discharge of the flood waters of the streams. The currents in Kaiaka Bay were studied by Belt, Collins, and Associates (1962a, 1962b) on two days in October and December 1961, "by surface floats of various kinds subsurface drogues, and dye. The results of the studies indicate that the floats and drogues were greatly affected directly by the wind. The records of the dye trajectories are very useful, however, in indicating current sets both in and outside the [Bay] .... In [the Bay], the current apparently sets continuously seaward, no doubt as a result of the [stream flow]. Velocities were about 0.1 to 0.3 knot. Outside the only measurements were on a rising tide, when the current set south westward with a velocity of 0.1 knot.... The currents in Kaiaka Bay are insufficient to prevent stagnation, as indicated by low oxygen content and high biochemical oxygen demand" (Laevastu, Avery, and Cox, 1964). Analyses by Belt, Collins and Associates in 1962 indicated, however, considerable pollution of the streams and Bay. In the common mouth of Kiikii and Paukauila Streams the median coliform concentration was 1450 and the maximum 40,000 MPN/100 ml. In the Bay, in general, the median was on the order of 1,500 and the maximum 3,700 MPN/100 ml except at the discharge of a ditch on the west shore when the median was 22,000 and the maximum 235,000 MPN/100 ml. The ditch was suspected of being the principal source of pollution. Other pollution indicators showed similar variations in concentrations, the maximum concentrations of 1,750 MPN/100 ml for streptococci, 90,000 MPN/100 ml for *E. coli*, 49.3 mg/l for nitrate nitrogen and 585 mg/l for suspended solids being at the discharge of the ditch.

Kaiaka Bay, from its location, and the stream estuaries, from their tidal response, must be Class A coastal waters. The analyses cited, however, indicate that at least in 1962 they did not meet the standards for this class.

Kaiaka Bay is used for bait fishing. Frederick Gross, Civil Engineer with Waialua Agricultural Company, observed that "they (fishermen) continue to come in for bait fish and have for many years, so it indicates that the waters are still suitable" (Department of Health, State of Hawaii, 1966b).

MOLOKAI

The island of Molokai (Fig. 31) consists of the tops of two volcanoes, West Molokai, projecting to an altitude of 1,381 feet above sea level, and the East Molokai, projecting to an altitude of 4,970 feet above sea level (Stearns and Macdonald, 1947).

The maximum average rainfall at the summit of East Molokai is probably about 200 inches per year. West Molokai is quite dry, with a maximum average of about 30 inches per year, and the rainfall on the leeward west coast averages less than 15 inches per year.

There are no perennial streams on West Molokai, and on East Molokai perennial streams are restricted to the central and eastern parts of the mountains, where they drain the high rainfall area. Some of the valleys on the north coast have been eroded so deeply that their streams are fed, in part, by dike springs. The toes of the major valleys on both coasts are submerged below sea level but most are filled with sediments, and along most of the south coast of the island there is a narrow sedimentary coastal plain. Offshore on the coast there is an estuarine coral reef.

The only bay estuaries are two on the north coast and east end of East Molokai. Associated with one is a stream-mouth estuary. On the south coast are a large number of fish ponds supplied with brackish water by springs and hence are of estuarine character.

Halawa Stream and Bay

Halawa Bay (Fig. 32A) on the north coast of Molokai near the eastern end of the island, is the drowned lower portion of the valley of Halawa Stream, and the stream itself is estuarine for a length of about 2,000 feet.

The headwaters of Halawa Stream are in the eastern end of the high-rainfall crest area of East Molokai. The average discharge at a gaging station at 200 feet altitude is about 19 mgd, and the minimum 0.7 mgd. (U. S. Geological Survey, 1961). There are no significant diversions of water.

The upper part of the valley is forested and the lower part in ranch use. The small village of Halawa in the lower valley is served by cesspools.

The alluvial fill of the valley is about 2,000 feet wide at its mouth. The beach at the mouth of the stream is composed of cobbles but another, 500 feet east, is composed of sand of both marine and terrestrial origin (Moberly and Chamberlain, 1964).

Halawa Bay has been designated as Class A coastal water, and considering its tidal character the stream estuary must be included in Class A also. No pollution of either the Bay or the stream have been reported, but there are no analyses to indicate whether their water quality meet the standards for the class.

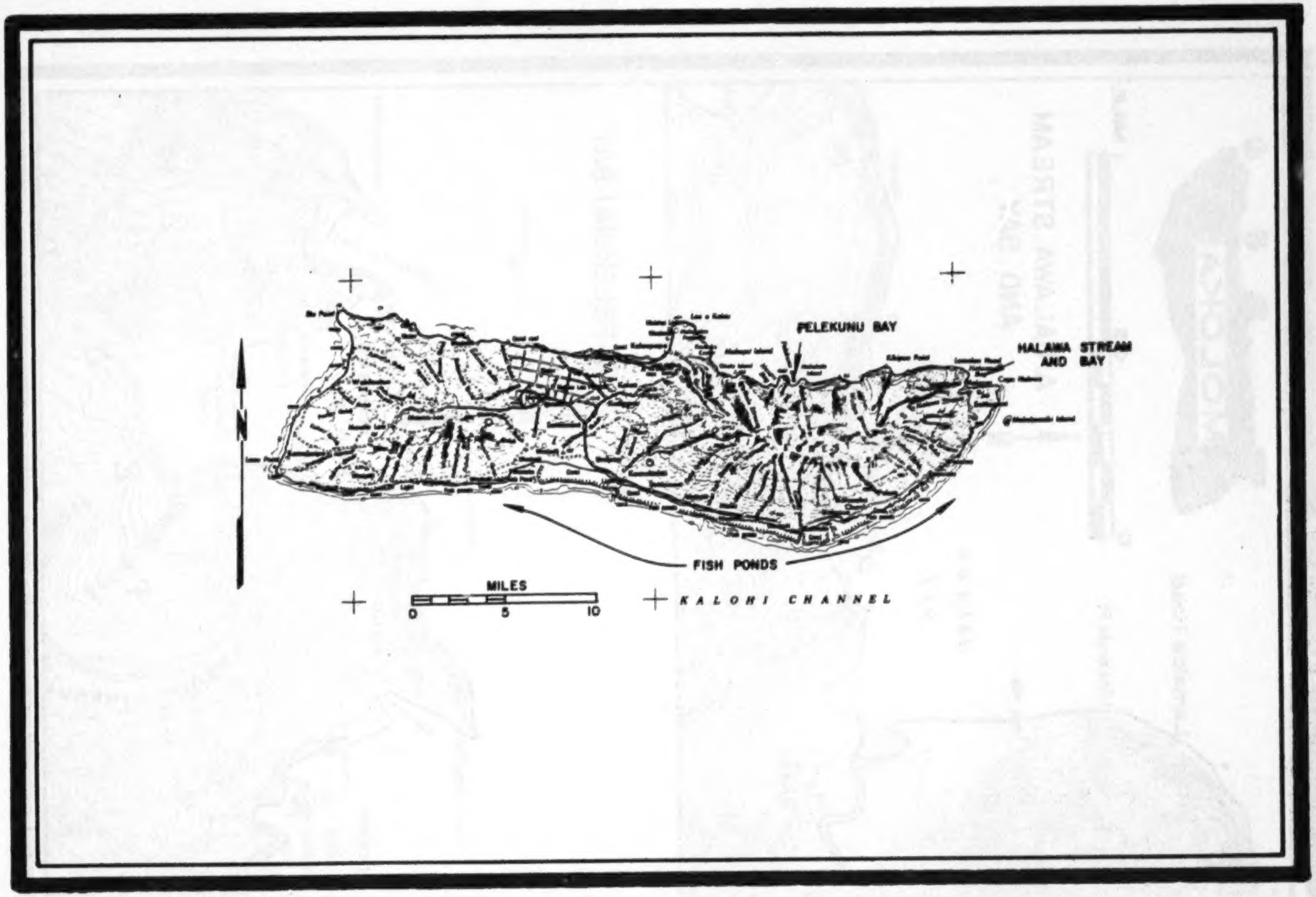


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FIGURE 31. ESTUARIES OF THE ISLAND OF MOLOKAI.

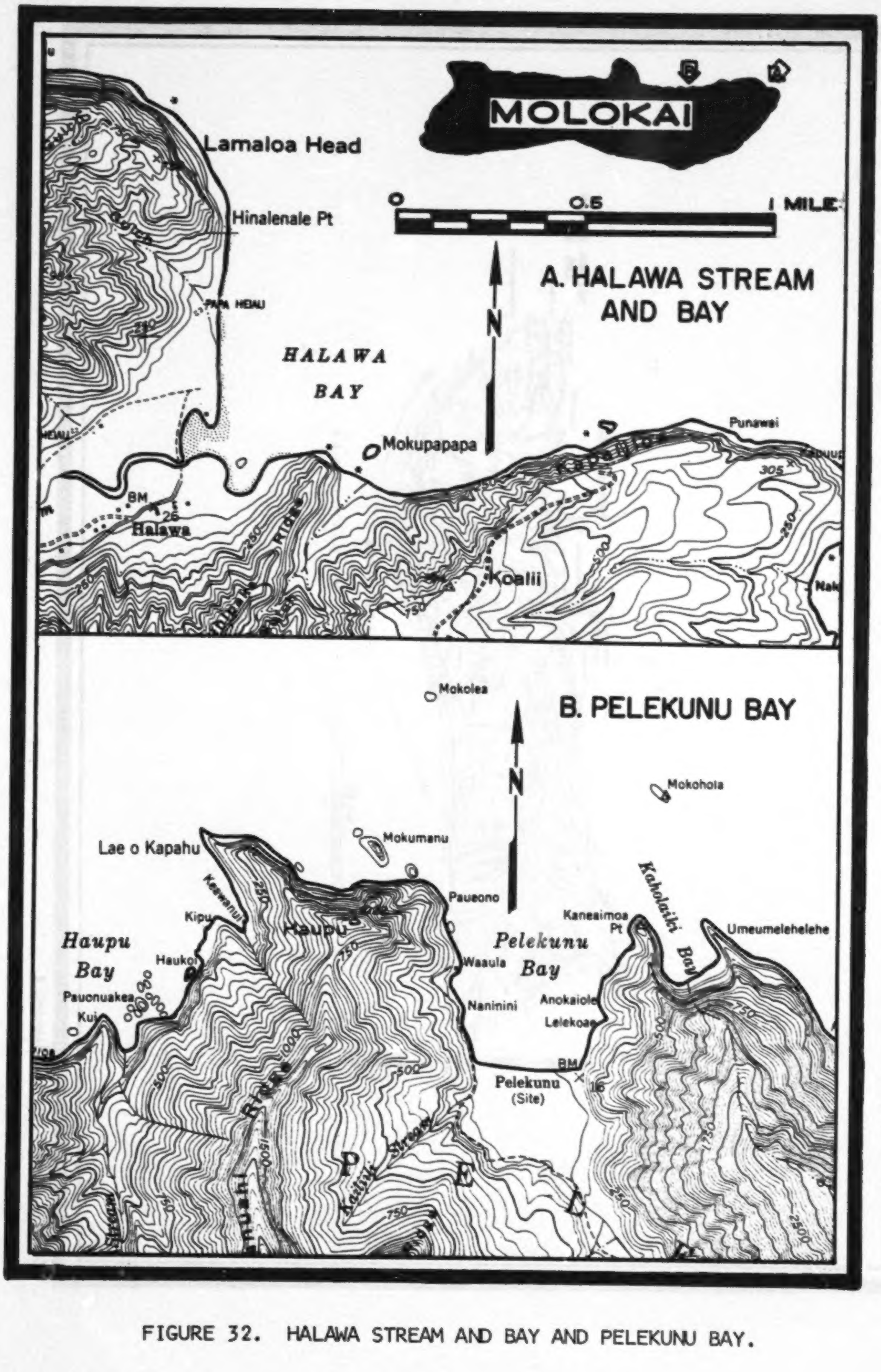


FIGURE 32. HALAWA STREAM AND BAY AND PELEKUNU BAY.

Pelekunu Bay

Pelekunu Bay (Fig. 32B) on the north coast of East Molokai is the drowned lower end of the valley of Pelekunu Stream, which heads in the high-rainfall crest area. The dry weather flow of the stream is augmented by dike springs. The mean discharge of the stream is about 11 mgd and the minimum about 1 1/2 mgd at a gaging station at 546 feet altitude (U. S. Geological Survey, 1961). At its mouth the mean flow must be very much greater but the minumum about the same. There are no diversions of water. There is a boulder beach at the head of the Bay.

Pelekunu Bay is within the northern Molokai coastal waters designated as Class AA. The valley is uninhabited and there are no potential sources of pollution except the mud introduced by flood flows of the stream. It seems likely that the water quality in the Bay meets the high standards for Class AA.

Fishponds of South Molokai

Along the south coast of Molokai are at least 40 fish ponds of prehistoric construction, mostly formed by surrounding part of the reef flat, next to the shore, by a wall of rocks, or in a few cases occupying depressions in the coastal plain. Although ponds are not supplied with water by streams, many are brackish, as the result of fairly fresh water by diffuse ground-water seepage or easily recognizable springs, and hence have an estuarine character essential to the cultivation of mullet. Only a section of this coast with its ponds is shown in Figure 33.

Most of the fish ponds are now badly silted, and in fact mud has accumulated on the surface of the reef along most of the coast. Mangrove swamps are encroaching in places. The source of the mud is undoubtedly the slopes inland. It is uncertain to what extent the silting of the fish ponds is a result of accelerated erosion inland and to what extent it simply represents poor maintenance. It is commonly supposed that accelerated erosion has resulted from grazing on the slopes, but climatic change might also be a causative factor. The ecology of the fish ponds is under current investigation by the Oceanic Institute of Honolulu.

From the fact the the fish ponds are tidal, they must fall in Class A of coastal waters, although it is questionable whether the applicability of the water quality standards to fish ponds was fully considered when they were adopted. No analyses are known that indicate the quality of their waters in relation to the standards for Class A waters.

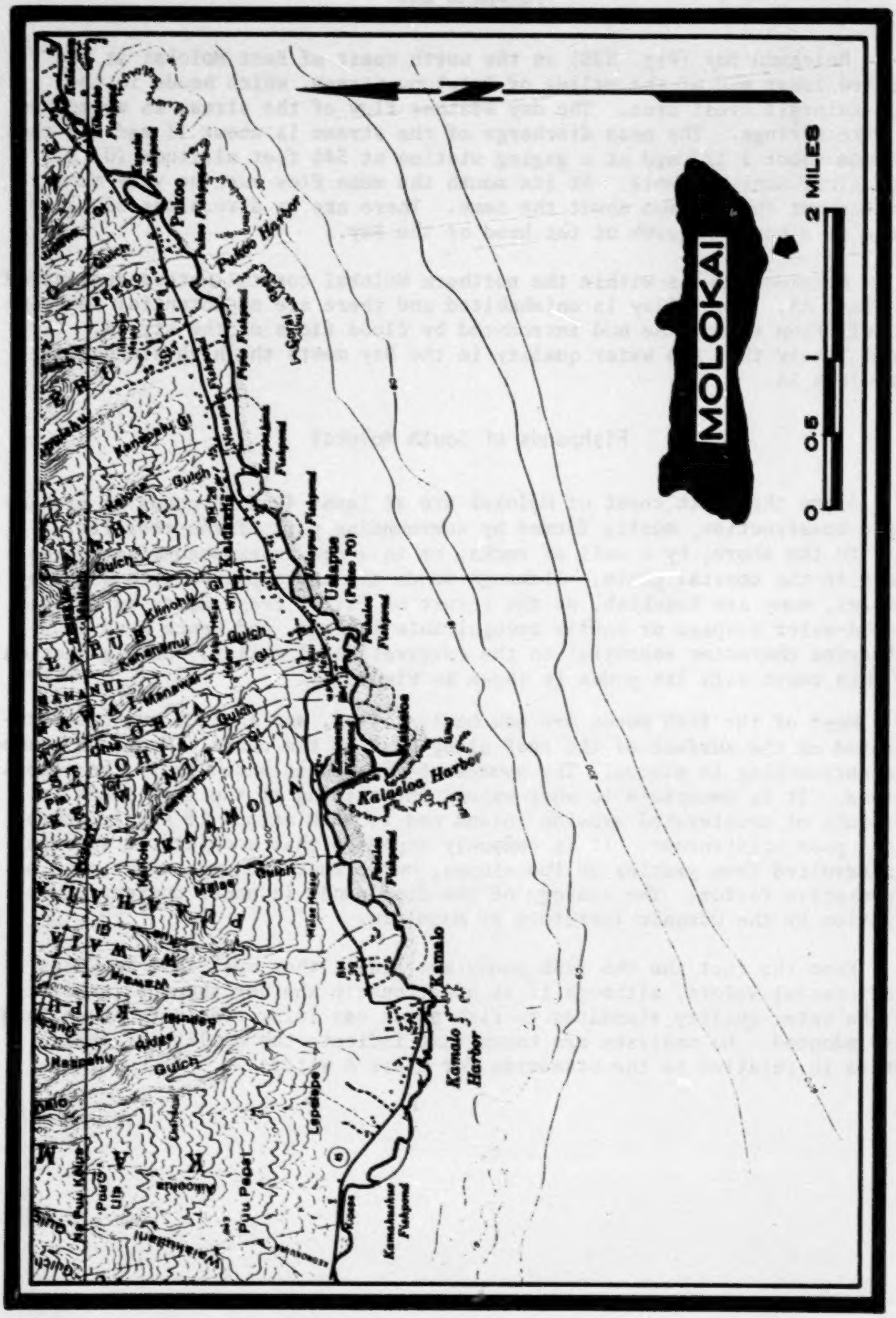


FIGURE 33. FISHPONDS BETWEEN KAMALO AND PUKOO.

LANAI

The island of Lanai is the top of a single volcano (Stearns, 1940b), reaching an altitude of 3,370 feet. The Palawai Basin, in the south-central part of the island, is the still undrained caldera of the volcano. The rainfall on the highland to the northeast averages about 35 inches per year. On the coasts, the average is only about 10 inches per year. No perennial streams reach the coast of the island and although there are some valleys of moderate size inland, there are no significant bays at their mouths. Along the north and east coast there is a narrow coastal plain. There are no estuaries on the island.

KAHOOLAWE

Kahoolawe is top of a single volcano, which projects only 1,427 feet above sea level (Stearns, 1940b). The average rainfall is probably only about 25 inches per year. The surface is deeply weathered, but there are no perennial streams, and wind accounts for much of the erosion. The principal bays are of structural origin. There are no estuaries on the island.

MAUI

The island of Maui (Fig. 34) consists of two volcanoes, West Maui, 5,788 feet altitude, and Haleakala on East Maui, 10,025 feet altitude (Stearns and Macdonald, 1942).

The basaltic shield of the West Maui volcano was capped by andesitic and in places trachytic lavas. This volcano has been deeply eroded, although its original shield form, much steeper than normal for a Hawaiian volcano, is preserved in accordant ridges. It has been deeply submerged, but except on the north coast the submerged valleys have been refilled by sediments and locally on the west coast by post-erosional volcanoes, and a coastal plain with a smooth shoreline has been developed along most of the west and southwest coasts. On the eastern flank of the volcano, the sediments have formed fans agiinst the slope of the later-developing Haleakala volcano.

Haleakala volcano was last active on its southwest rift zone about 1790. Three large valleys, Keanae Valley on the northeast coast and Kipahulu and Kaupo Valleys on the southeast coast, have been filled with post-erosional lavas and sediments which form fans at their mouths. Late lavas have considerably extended the east end of the island, burying any erosional valleys that may once have existed there, and to a lesser extent the southwest point of Haleakala.

The Maui Isthmus between the two volcanoes, is underlain mainly by Haleakala lavas. Narrow sedimentary coastal plains have been formed, however, along both its north and south coasts.

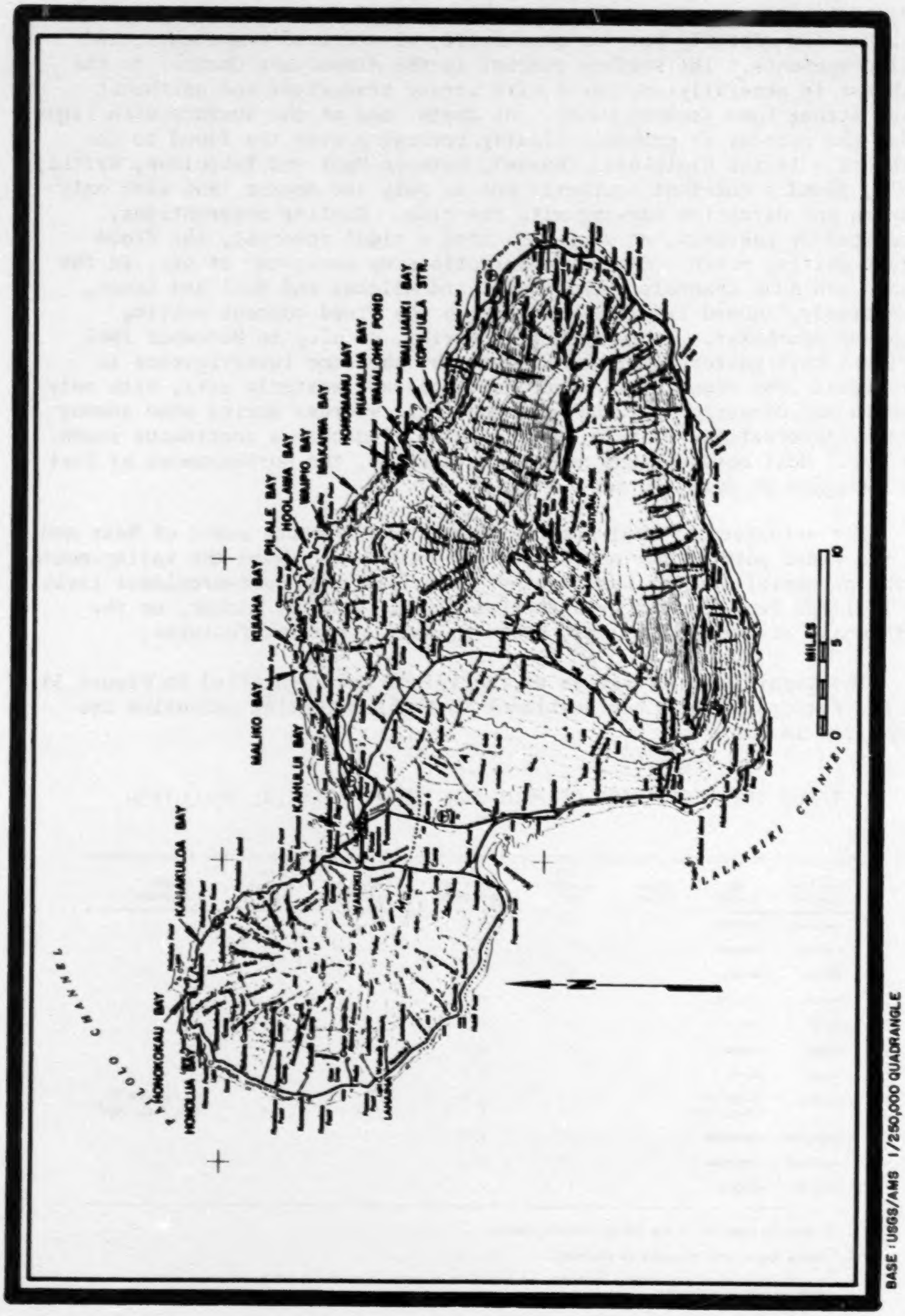
The maximum rainfall on the windward flank of East Maui at about 3,000 feet elevation is over 300 inches per year. At the summit, the average is less than 30 inches, and on the leeward coast the average less than 10 inches per year.

The maximum rainfall on West Maui is in the summit area where the average annual rate is over 400 inches per year. The rainfall decreases to less than 40 inches per year on the windward coast and less than 15 inches per year on the leeward coast.

Perennial streams drain radially in all directions from the high-rainfall summit area of West Maui, but are almost completely restricted on East Maui to the northern slope. Many of the streams on the northern slope of East Maui are fed by perched springs as well as by overland flow in the high-rainfall area and those in Keanae Valley are fed by dike springs. The high infiltration capacity of the late lavas at the eastern end of the island has prevented the development of perennial streams and valleys there, even though the rainfall is high.

The dry-weather flows of the only perennial streams on the south coast of East Maui, those in Kipahulu and Kaupo Valleys, are supplied by dike and perched springs.

The sparce and in some ways conflicting observations of nearshore currents around Maui (Laevastu, Avery, and Cox, 1964; Wyrtki, *et al.*,



BASE: USGS/AMS 1/250,000 QUADRANGLE

FIGURE 34. ESTUARIES OF THE ISLAND OF MAUI.

1967) indicate a complicated pattern resulting from the combination of the generally westerly but variable drift, wind-driven components, and tidal components. The surface current in the Alenuihaha Channel to the southeast is generally southwest with strong tradewinds and northeast during strong kona (south) winds. At depth and at the surface with light winds, the current is probably tidally reversing with the flood to the northeast. In the Alalakeiki Channel, between Maui and Kahoolawe, Wyrtki, *et al.*, found a constant southerly set in July and August 1966 with only strength and direction varying with the tide. Earlier observations, summarized by Laevastu, *et al.*, indicated a tidal reversal, the flood current setting north. Similar observations by Laevastu, *et al.*, in the Pailolo and Auau Channels between Maui and Molokai and Maui and Lanai, respectively, showed tidal reversals with the flood current setting south and southeast. Measurements by Wyrtki, *et al.*, in December 1965 confirmed this pattern, but measurements by the same investigators in July-August 1966 showed continuous northerly and westerly sets, with only strength and direction varying with the tide, whereas during some summer periods, observations at Mala, near Lahaina, indicate a continuous southeast set. Most observations near Pauwala Point, the northernmost of East Maui indicate an easterly set.

The estuaries of Maui are restricted to the north coast of West Maui and the older part of the north coast of East Maui, where the valley-mouths of the perennial streams have neither been filled by post-erosional lavas nor isolated from the sea by a coastal plain. Kahului Harbor, on the north coast of the Isthmus has, however, some estuarine features.

The significant estuaries of the island are identified in Figure 34 and the factors of land use pertinent to their potential pollution are summarized in Table 14.

TABLE 14. ESTUARIES OF MAUI AND THEIR POTENTIAL POLLUTION.

ESTUARY SYSTEM	BAY ESTUARY	STREAM ESTUARY	WATER DEVELOP-MENT	AGRICULTURAL DEVELOPMENT	INDUSTRIAL DEVELOPMENT	URBAN DEVELOP-MENT	ESTUARY DEVELOPMENT
HONOMANU	HONOMANU		I[1]				
MAKAIWA	MAKAIWA		I				
WAIPIO	WAIPIO		I	R			
HOOLAWA	HOOLAWA		I	R			
PILALE	PILALE		I	R			
KUIAHA	KUIAHA		I	R, P			
MALIKO	MALIKO			S, P			
KAHULUI	KANAHA PD			S, R			SEE FOOTNOTE [2]
	KAHULUI HBR.			S	P, E, M	S, C	H, R, (O_P), (O_R)[3]
KAHAKULOA	KAHAKULOA			R, T			
HONOKAHAU	HONOKAHAU		I	P		C	
HONOLUA	HONOLUA		I	P			

[1] REFER TO PAGES 18 - 20 FOR THE KEY TO THESE SYMBOLS.

[2] KANAHA POND IS USED AS A WILDLIFE SANCTUARY.

[3] THE WAILUKU SEWER OUTFALL (PRIMARY TREATMENT) AND KAHULUI SEWER OUTFALL (RAW SEWAGE) ARE IN THE OCEAN, RESPECTIVELY, WEST AND EAST OF THE HARBOR.

Estuaries of Northeast Coast of East Maui

The irregular coastline of the northeast coast of East Maui is the result of both marine and stream erosion of the older lavas of Haleakala volcano, together with the formation of fans of post-erosional lavas at the mouth of Keanae Valley and east of Nahiku. In the development of many of the bays, it is difficult to establish the relative importance of differential marine and stream erosion and valley submergence. The shoreline generally consists of cliffs from 100 to 400 feet high and some of the streams drop in waterfalls to the sea. However, waterfalls are a normal feature of Hawaiian valley development, hence even some of the coastal falls may be partly of stream-erosional origin. Most of the bays are small, with dimensions of less than 1,000 feet, and only the more notable ones, in whose development stream erosion has probably been a major element, will be mentioned here.

Wailua Bay (Fig. 35) consists of two arms, Wailuanui, which has resulted primarily from the development of an old, post-erosional fan of lavas emerging from Keanae Valley to the east, and Wailuaiki, which is the drowned valley of the East and West Wailuaiki Streams, much modified by marine erosion. The shallow identation of Nuaailua Bay resulted from the drowning of valley of Nuaailua Stream, much modified by marine erosion. Honomanu Bay (Fig. 36), the drowned valley of Honomanu Stream, is the best developed bay estuary on the coast. The narrow indentation of Makaiwa Bay is the drowned valley of Oopuola Stream. Waipio Bay (Fig. 37) may be in part the drowned valley of Waipio Stream, but it has been much enlarged by marine erosion. Hoolawa Bay is the drowned valley of Hoolawa Stream. Pilale Bay is the drowned valley of Kakipi Stream. Kuiaha Bay (Fig. 38) is the drowned valley of Kuiaha Stream.

All of the streams named above are intercepted inland by one or more ditch-tunnel systems, and their normal flows at the points of interception diverted for irrigation on the Maui Isthmus. However, most of the streams, particularly Honomanu and those farther southeast, receive substantial spring discharge below ditch level. All of the streams originate in forest lands and the entire watersheds of the eastern streams are in forest. Parts of Waipio, Hoolawa, and Kakipi Valleys pass through ranch lands and Kuiaha Valley through pineapple fields as well.

There are boulder beaches at the heads of some of the bays and a beach of boulders and sand of terrestrial origin in Honomanu Bay.

The only significant stream-mouth estuaries on this coast are that of Kopiliula Stream (Fig. 35) southeast of Wailuaiki Bay, and the Waialohe Pond at the mouth of Piinaau Stream (Fig. 35). According to the topographic map, both are well separated from the sea by beaches. The entire valley of Kopiliula Stream is entirely in forest lands, as is the valley of Piinaau Stream. The village of Keanae, served by cesspools, is located on the fan of the most recent post-erosional flow which forms the northshore of the Waialohe Pond.

These estuaries fall within the coastal waters on the northeast coast of Maui which have been designated as Class AA. No reports of pollution have been found in any of their waters. Because of the absence

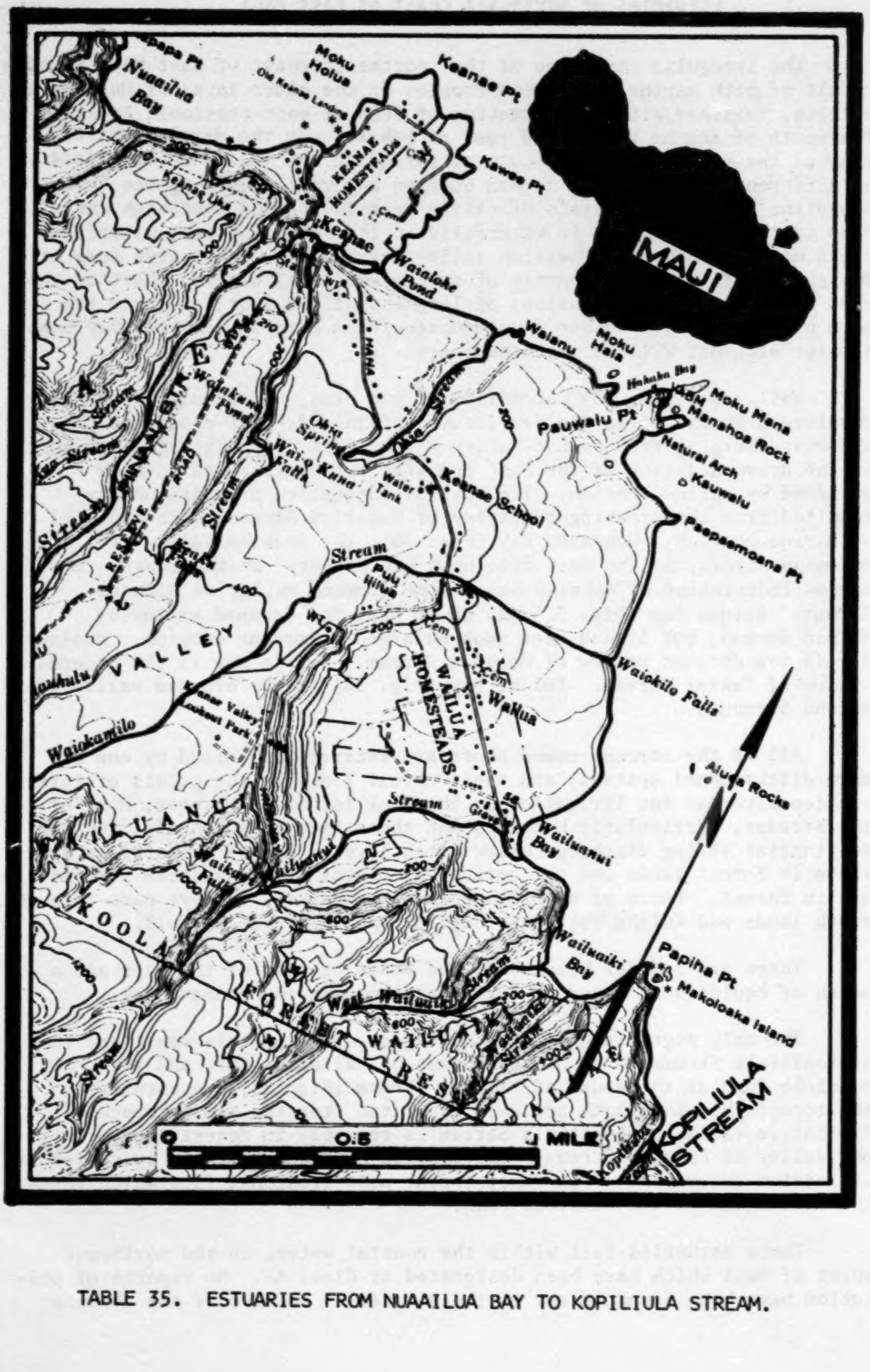


TABLE 35. ESTUARIES FROM NUAAILUA BAY TO KOPILIULA STREAM.

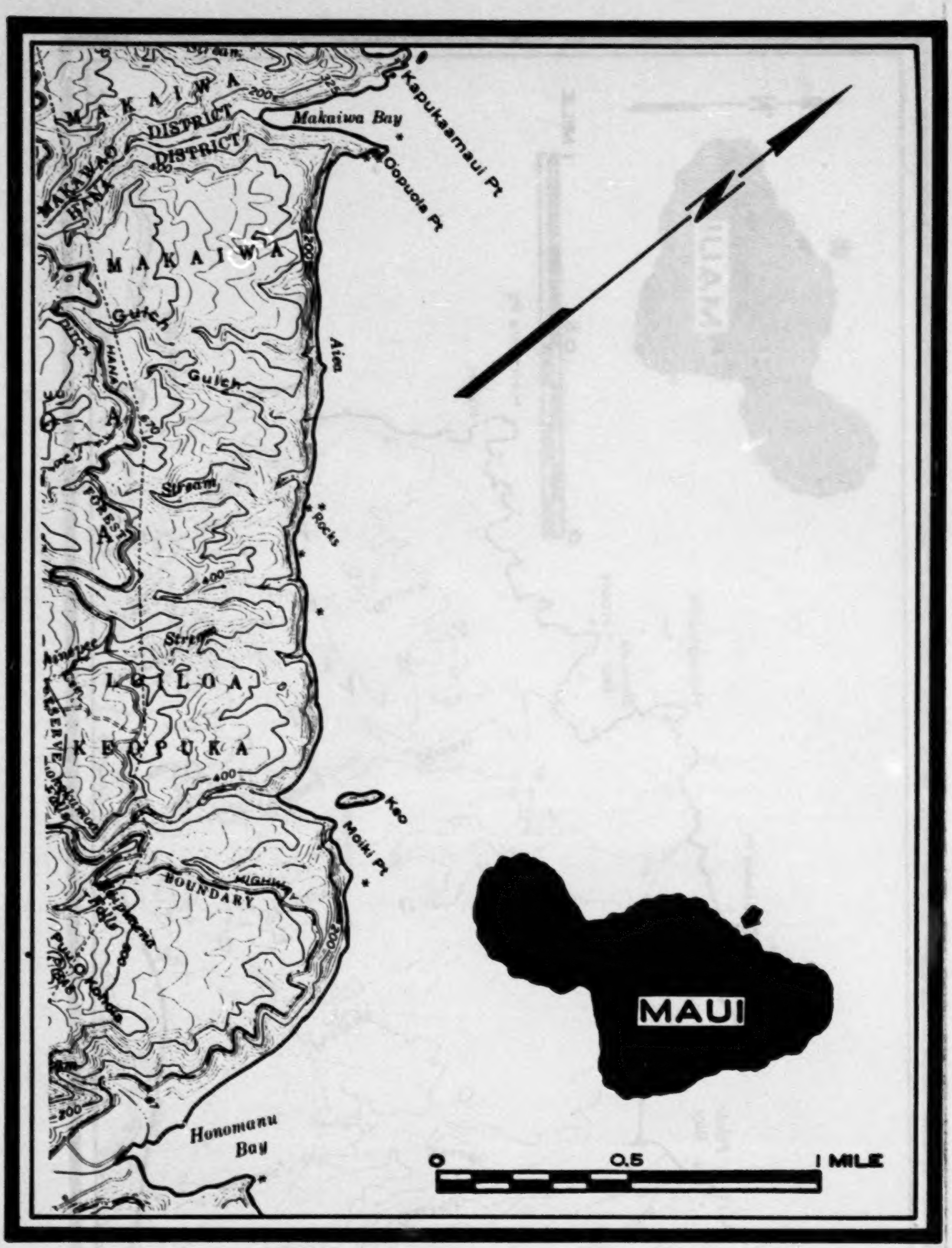


FIGURE 36. ESTUARIES FROM HONOMANU BAY TO MAKAIWA BAY.

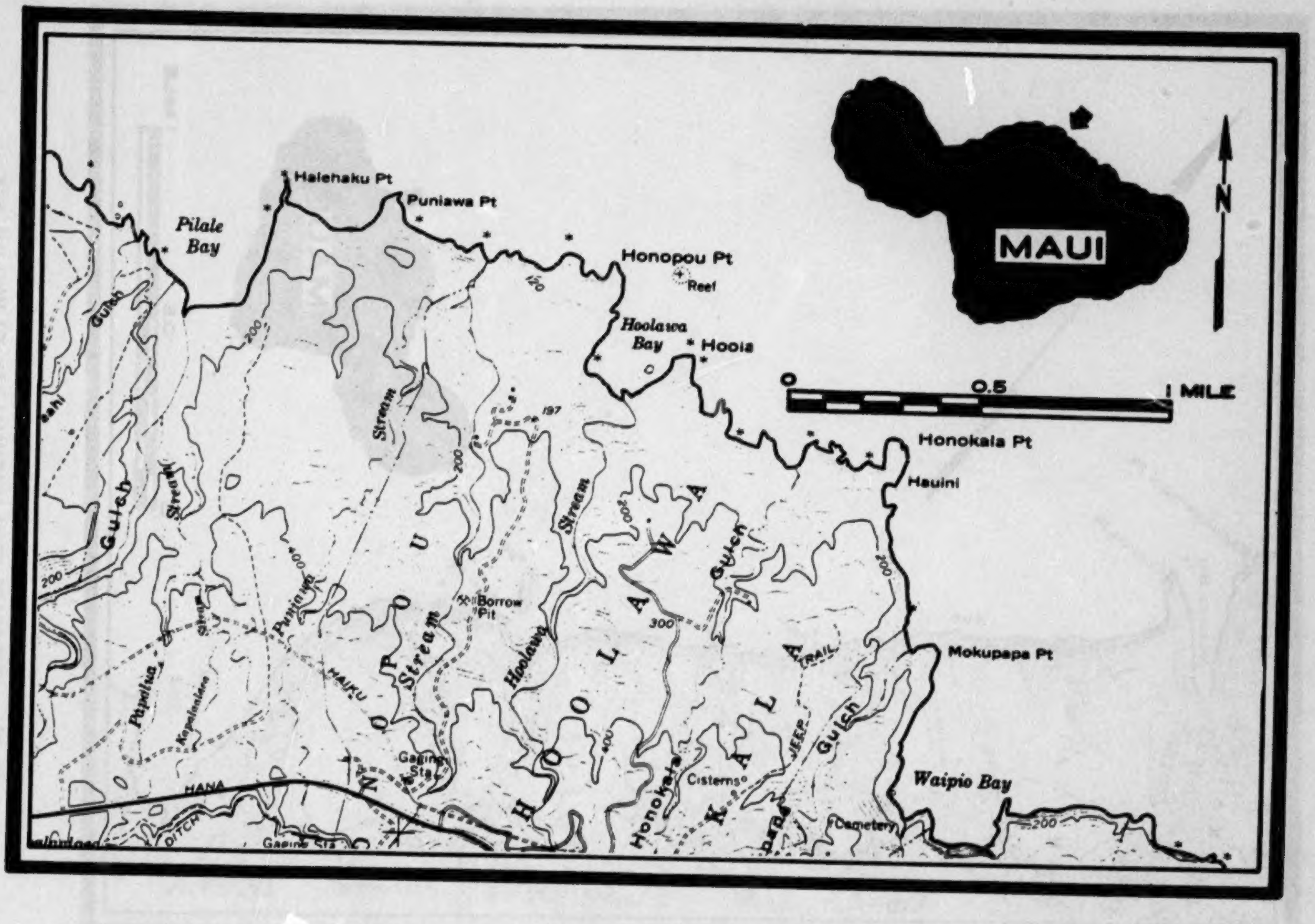


FIGURE 37. ESTUARIES FROM WAIPIO BAY TO PILALE BAY.

of significant sources of pollutants and the excellent mixing conditions expectable in the open bays, it is quite likely that they meet the Class AA standards. However, there are no analyses to prove this for the bays or for the streams either. There are no likely sources of pollution for the Kopiliula Stream estuary and the flow of Piinaau Stream may be sufficient to flush the Waialohe Pond so that no significant pollution occurs there.

Maliko Bay

Maliko Bay (Fig. 38), on the northwest coast of East Maui, is a small but typical bay estuary, consisting of the drowned mouth of Maliko Gulch. Maliko Stream, originating at the west edge of the high-rainfall belt on the windward flank of Haleakala and not fed by substantial springs, has only a very small dry-weather flow that is diverted inland for irrigation. Hence, the summer discharge at the coast is negligible. The stream discharges to the Bay through a beach of boulders and mainly terrestrial sand.

The headwaters of the stream are in forest lands, the middle course in ranch land, and the lower course between cane and pineapple lands. The Bay is open to the waves, mixing conditions are good, and pollution is probably not a problem.

From its location, the Bay must be in Class A of coastal waters. No analyses are available to determined whether its waters meet the standards for that Class.

Kahului Harbor

Neither Kahului Harbor (Fig. 39) nor the more inclusive Kahului Bay is a true estuary. The Bay is simply the reentrant on the north coast of the island of Maui between the slopes of the two volcanoes, Haleakala and West Maui. The harbor is that part of the head of the Bay which has been protected by breakwaters and improved by dredging. Kahului Harbor is included in the discussion here because it is the principal harbor of Maui and because it shares some pollution problems with some of the true Hawaiian estuaries.

No fresh-water streams or significant springs enter the harbor, although there must be some fresh-water seepage into the harbor from the basal ground-water body inland. Some storm drains enter the harbor, but the sanitary sewage of the nearby towns is disposed of into the Bay through two outfalls outside of the Harbor. The outfall serving the town of Kahului empties into the Bay at the base of the east breakwater and the one serving the town of Wailuku empties into the Bay a quarter mile west of the west breakwater.

Wastes from the Maui Pineapple Company cannery are discharged through the two sanitary sewer outfalls, principally that servicing Wailuku.

The Maui Electric Company thermal power plant which is located near the base of the east breakwater draws salt water for cooling from wells

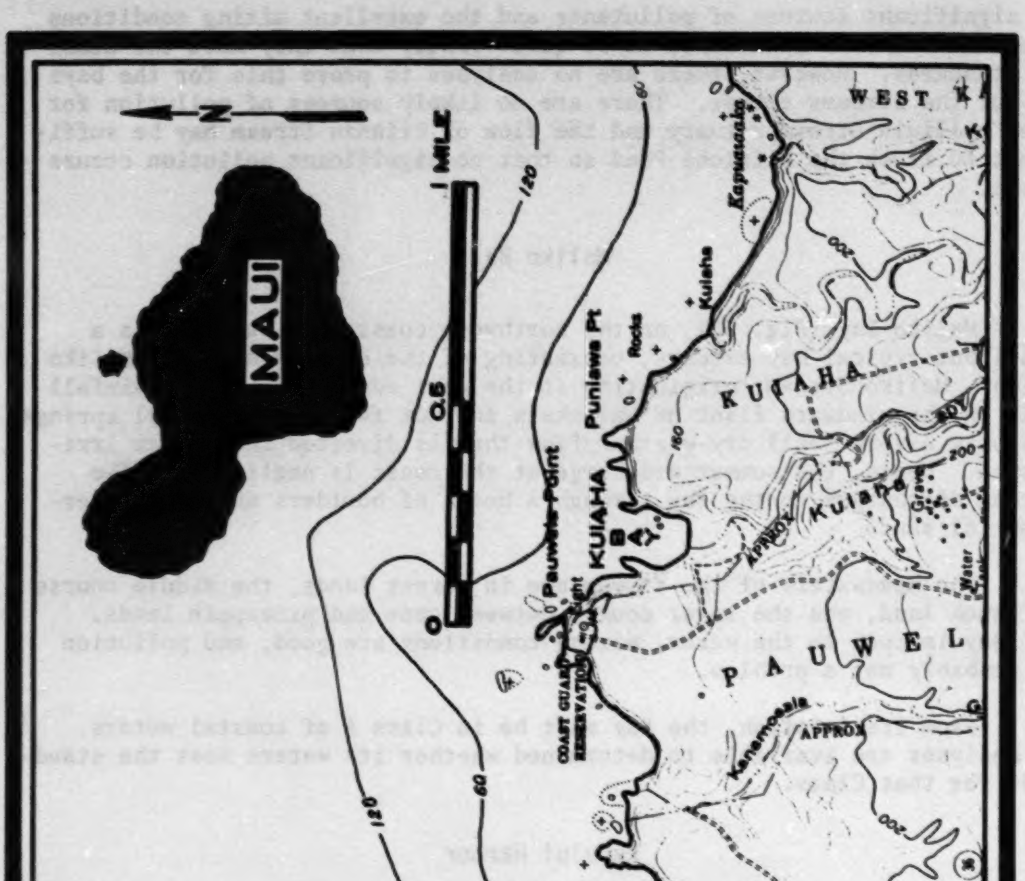


FIGURE 38. KUIAHA BAY AND MALIKO BAY.

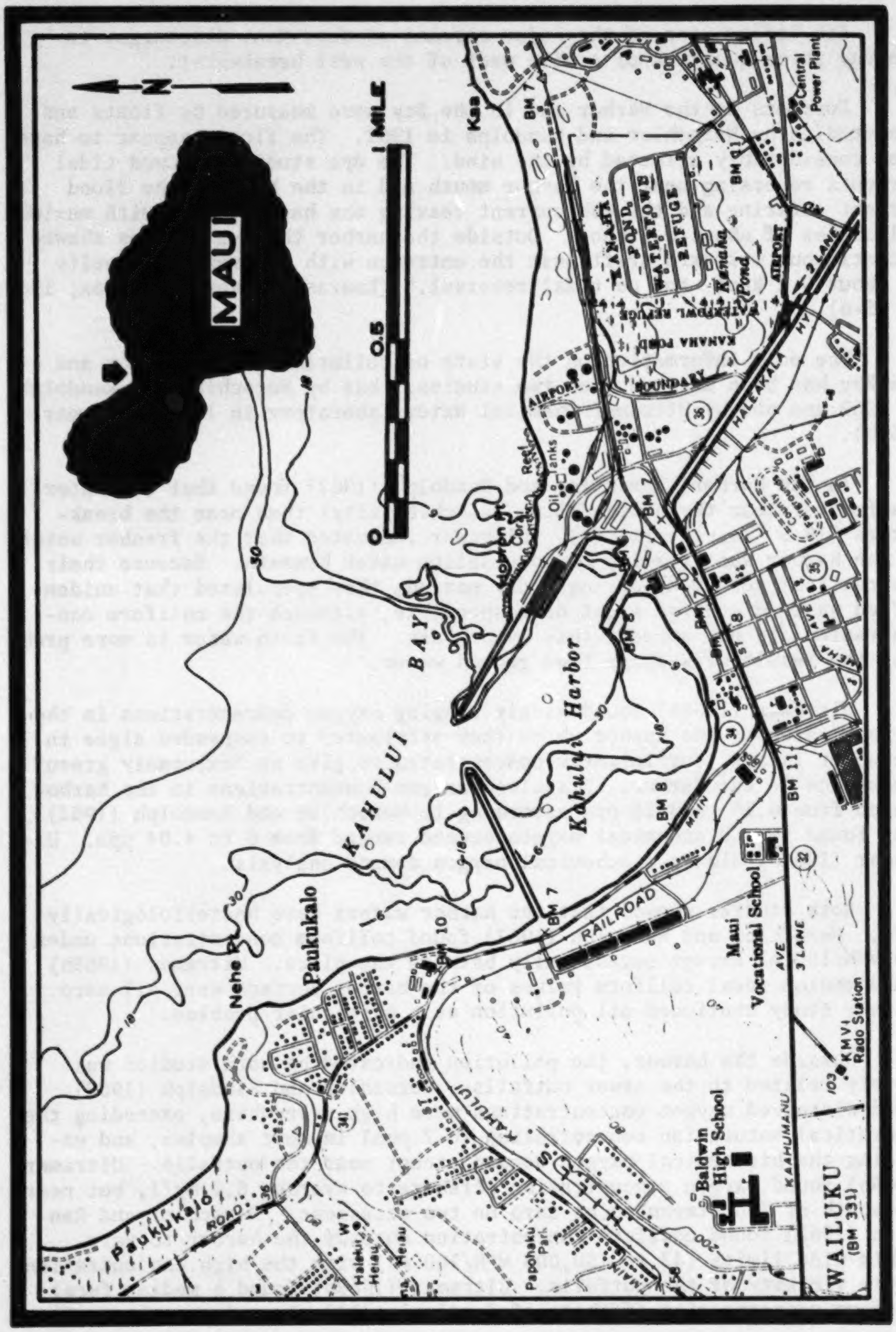


FIGURE 39. KAHULUI HARBOR.

and disposes of this water at the sea surface outside the Harbor.

Iao Stream, one of the major streams of West Maui discharges to the Bay three-quarters of a mile west of the west breakwater.

Currents in the Harbor and in the Bay were measured by floats and dye studies by Herschler and Randolph in 1962. The floats appear to have been considerably affected by the wind. The dye studies "showed tidal currents reversing near the harbor mouth and in the harbor, the flood current entering and the ebb current leaving the harbor, each with maximum velocities of about 0.3 knot. Outside the harbor the dye studies showed a continuous westward drift past the entrance with an average velocity of about 0.2 knot and no tidal reversal." (Laevastu, Avery, and Cox, 1964, p. 55-6).

The only information on the state of pollution of the Harbor and the Bay has been derived from two studies, that by Herschler and Randolph in 1962 and one by Ultramar Chemical Water Laboratory in 1968 (Ultramar, 1968b).

In the Harbor, Herschler and Randolph (1962) found that the water was fresher near the shore (13.0 °/₀₀ chlorinity) than near the breakwaters (18.5 °/₀₀ chlorinity). Ultramar indicated that the fresher water in the harbor was floating on more saline water beneath. Because their observations were made during a dry period, they speculated that unidentified waste discharge might be responsible, although the coliform concentration did not support this hypothesis. The fresh water is more probably the result of seepage from ground water.

Ultramar (1968b) found widely ranging oxygen concentrations in the surface water of the harbor which they attributed to suspended algae in the upper layers, sufficiently concentrated to give an "extremely green" appearance to the harbor. Dissolved oxygen concentrations in the harbor ranged from 6.16 to 8.28 ppm according to Herschler and Randolph (1962). They found that biochemical oxygen demand ranged from 0 to 4.04 ppm. Ultramar (1968b) did no biochemical oxygen demand analysis.

Both studies showed that the harbor waters were bacteriologically safe. Herschler and Randolph (1962) found coliform concentrations under 100 MPN/100 ml except occasionally between the piers. Ultramar (1968b) found median fecal coliform values of the harbor surface were all zero. Neither study mentioned oil pollution as a particular problem.

Outside the harbor, the pollution indicated by both studies was clearly related to the sewer outfalls. Herschler and Randolph (1962) found dissolved oxygen concentrations were high everywhere, exceeding the theoretical saturation concentration (6.7 ppm) in most samples, and exceeding the biochemical oxygen demand except near the outfalls. Ultramar (1968b) found oxygen concentration offshore to average 6.2 mg/l, but near the mouth of Iao Stream to be zero on two occasions. Herschler and Randolph (1962) found coliform concentration outside the harbor to vary within wide limits (43 to 150,000 MPN/100 ml) with the high concentrations in the vicinity of the outfalls. Ultramar (1968b) found a median fecal coliform concentration offshore of 2 colonies/100 ml, and a maximum of

23,700 colonies/100 ml, but median and maximum near the Kahului outfall of 12,000 and 472,730 colonies/100 ml, respectively.

Kahului Harbor is designated as a Class B coastal water. The analyses available suggest that the quality of water meets the standards for that Class, although outside the harbor, where the waters are supposed to be in Class A, the quality is poorer and clearly would not meet the standards.

A half mile east of the east breakwater of Kahului Harbor is Kanaha Pond, a bird refuge, which occupies a series of depressions in the weathered Haleakala lavas. The pond is fed by surface drainage and groundwater seepage, and discharges to the sea by overflow of a beach ridge only during flood periods. The pond has a pronounced odor. Drainage from a dairy area to the south may introduce some pollution, but the major pollution of the pond may be entirely natural.

Still further east there is an oxidation pond that serves the airport, but this discharges to the sea through a drainage ditch.

Kahakuloa Bay

Kahakuloa Bay, on the northeast coast of West Maui, is the drowned lower end of the valley of Kahakuloa Stream (Fig. 40). The heawaters of the stream are in the rainy central area of West Maui, but the stable part of the stream flow is provided by dike springs down the valley. The mean discharge of the stream at the gaging station at 330-foot altitude is about 13 mgd, and the minimum discharge is 2 1/2 mgd (U. S. Geological Survey,11961).

Most of the valley is in forest, but taro is grown in the lower part. Part of the stream discharge is diverted for irrigation of the taro, but much of the diversion is returned to the stream. The village of Kahakuloa, served by cesspools, is located in the lower valley. There is a boulder beach at the head of the bay.

There are no records of pollution at Kahakuloa and it is doubtful that the Bay can be significantly polluted, except by mud following floods, because it is open to the waves and mixing conditions should be excellent. Kahakuloa Bay is within the zone on the northeast coast of West Maui designated as Class AA coastal waters. Although no analyses are available to prove the matter, it seems probably that the water quality of the Bay would meet the high standards of that class.

Honokohau Bay

Honokohau Bay, near the north point of West Maui, is the drowned lower part of the valley of Honokohau Stream (Fig. 41). The headwaters of the stream are in the rainy central area of the West Maui Mountains. A part of the flow of the stream is derived from dike springs and tunnels. The mean flow of the stream, at the only gaging station at 950 feet altitude, is about 5 mgd (Geological Survey, 1961). However, all of

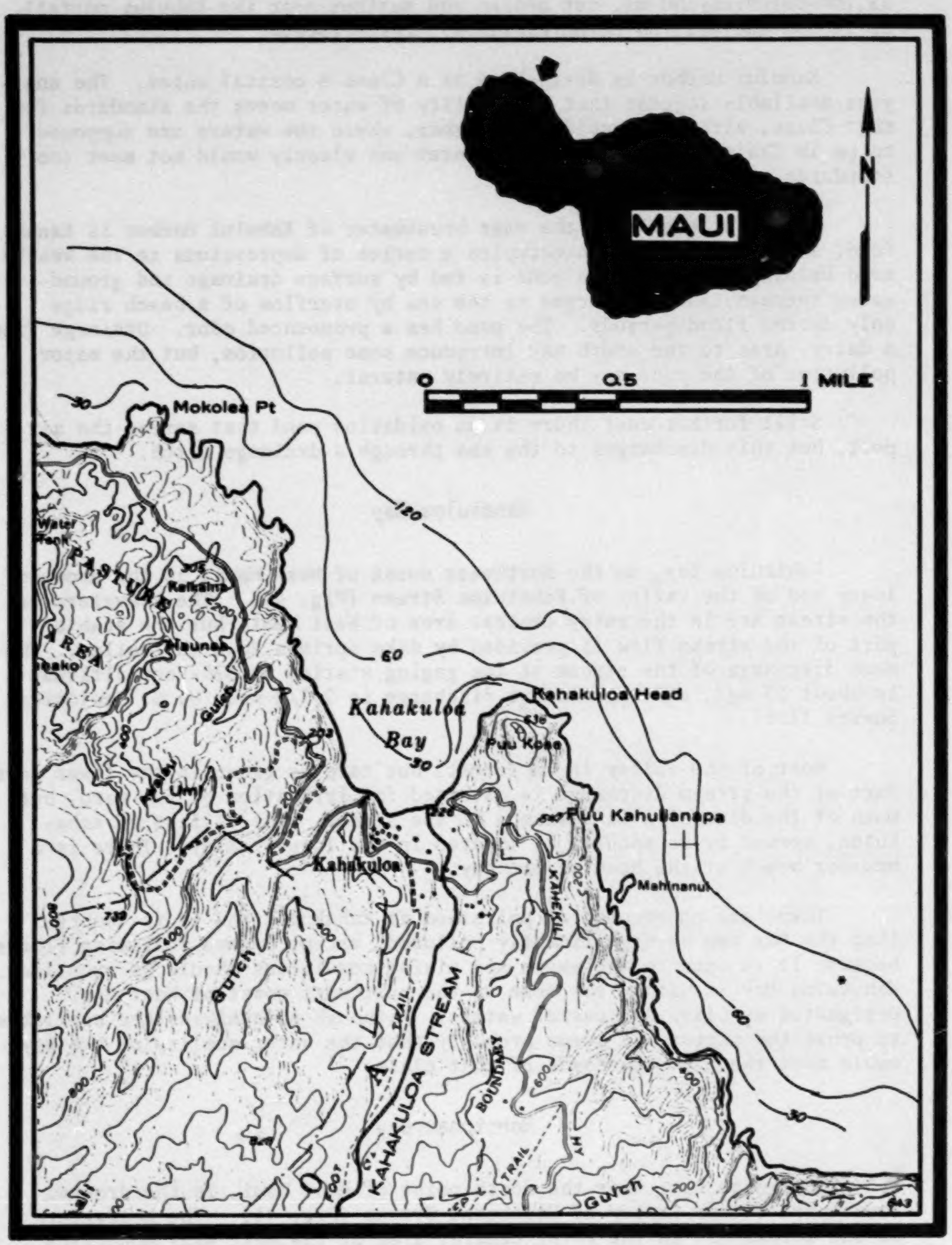


FIGURE 40. KAHAKULOA BAY.

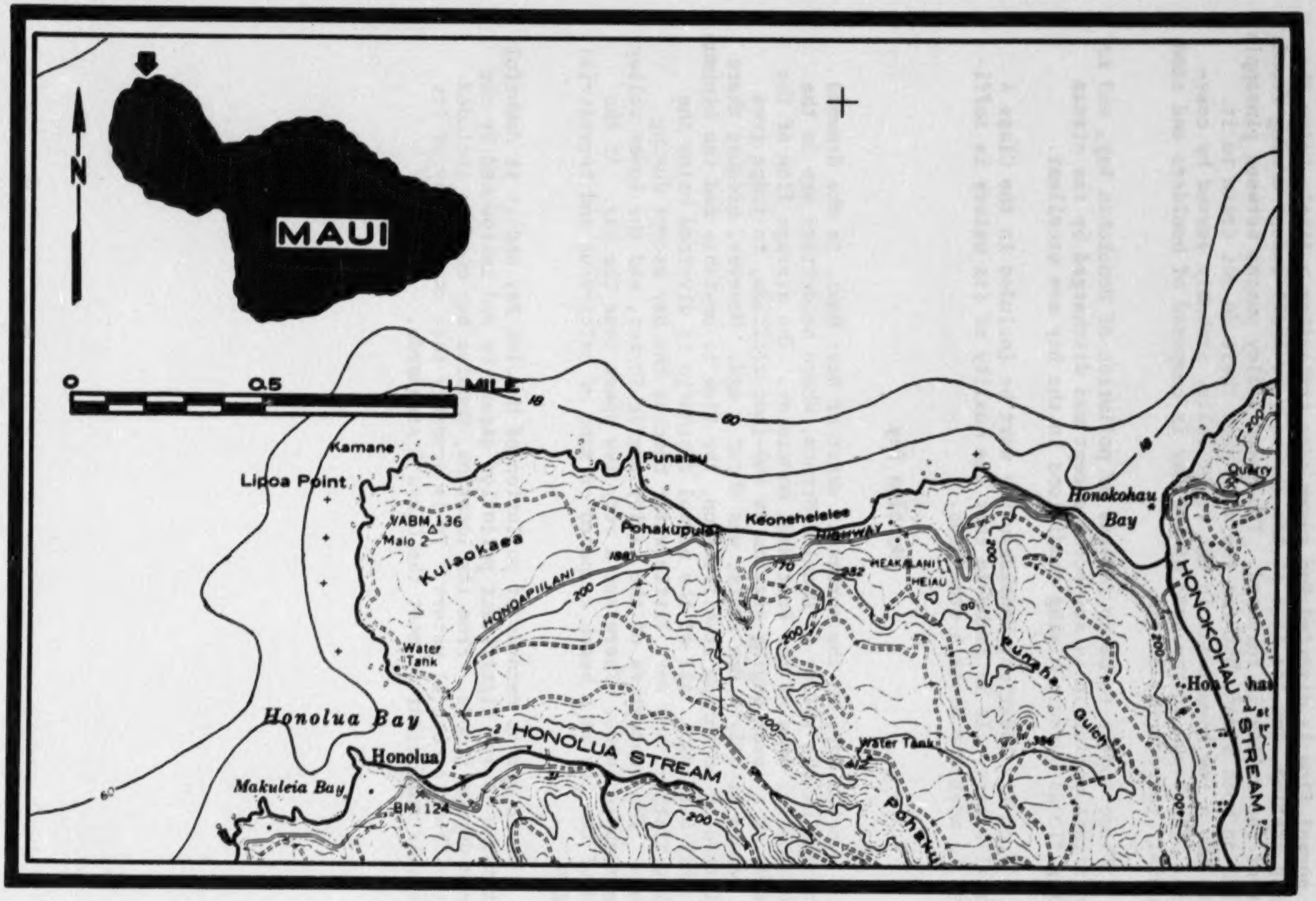


FIGURE 41. HONOKOHAU BAY AND HONOLUA BAY.

the normal flow is diverted for sugar cane irrigation a little below the gaging station, and the flow at the Bay is very small except during floods. Most of the valley is forested. The lower valley passes between pineapple fields on both sides, but for the most part these do not drain to it. There are a few homesteads in the lower valley probably served by cesspools. The beach at the head of the Bay is composed of boulders and sand of mainly terrestrial origin.

There appear to be no records of pollution of Honokohau Bay, and no significant pollution is suspected except mud discharged by the stream during floods because mixing conditions in the Bay are excellent.

From its location, Honokohau Bay must be included in the Class A coastal waters. It is probable that the quality of its waters is sufficient to meet the Class A standards.

Honolua Bay

Honolua Bay, on the northwest coast of West Maui, is the drowned lower end of the valley of Honolua Stream, whose headwaters are in the rainy central area of the West Maui mountains. The average flow of the stream, at a lower gaging station at 840-foot altitude, to judge from the record of only a few years, was about 6 mgd. However, because there is little or no spring stabilization, the flow is unstable and the minimum was only 0.15 mgd. All of the normal discharge is diverted below the gaging station, and very little water reaches the Bay except during floods. The headwaters of the valley are in forest, and the lower valley in pineapple lands. There are a very few homes near the Bay. At the head of the Bay is a beach composed of sand of calcareous and terrestrial origin.

There are no records of pollution of Honolua Bay and it is doubtful that there is any significant pollution except by mud introduced by the stream during floods. From its location, Honolua Bay must be included in the Class A coastal waters. It is probably that the quality of its waters is sufficient to meet the Class A standards.

HAWAII

The island of Hawaii (Fig. 42) is composed of five volcanoes, Kohala (alt. 5,505 ft), Mauna Kea (alt. 13,784) ft), Hualalai (alt. 8,251 ft), Mauna Loa (alt. 13,679 ft), and Kilauea (alt. 4,040 ft) (Stearns and Macdonald, 1946). The Kohala volcano at the north end of the island has long been dormant, and large valleys have been eroded on its windward flanks and partially refilled with sediments as the result of submergence. Mauna Kea has not been active in historic times and valleys have been eroded on its windward side that have been somewhat submerged and refilled with sediment. Hualalai was last active in the 1850's, and Mauna Loa and Mauna Kea are in frequent activity. They have been significantly eroded only locally.

There are maximum rainfall belts near the summit of the Kohala mountains (average about 200 inches/yr), on the windward flanks of Mauna Loa and Mauna Kea (average about 250 inches/yr), on the southeast flank of Mauna Loa (average about 160 inches/yr), and on the southwest flank of Hualalai (average about 120 inches/yr). The average rainfall on the windward coast is generally more than 60 inches/yr and is over 100 inches/yr on much of the east coast of Mauna Kea. On the leeward coasts the average is generally less than 30 inches/yr and is less than 10 inches/yr on the northwest coast of Mauna Kea.

Partly because of the low rainfall inland in many areas, and partly because of the very high infiltration capacity of the fresh lavas, no perennial streams reach the coast except on the northeast coast from Pololu to Hilo.

Currents reversing with the tide have been observed on the west and southeast coasts of the island, but on the northeast coast the current sets almost uniformly to the northwest except in Hilo Bay where there is sometimes a southerly eddy (Laevastu, Avery, and Cox, 1964).

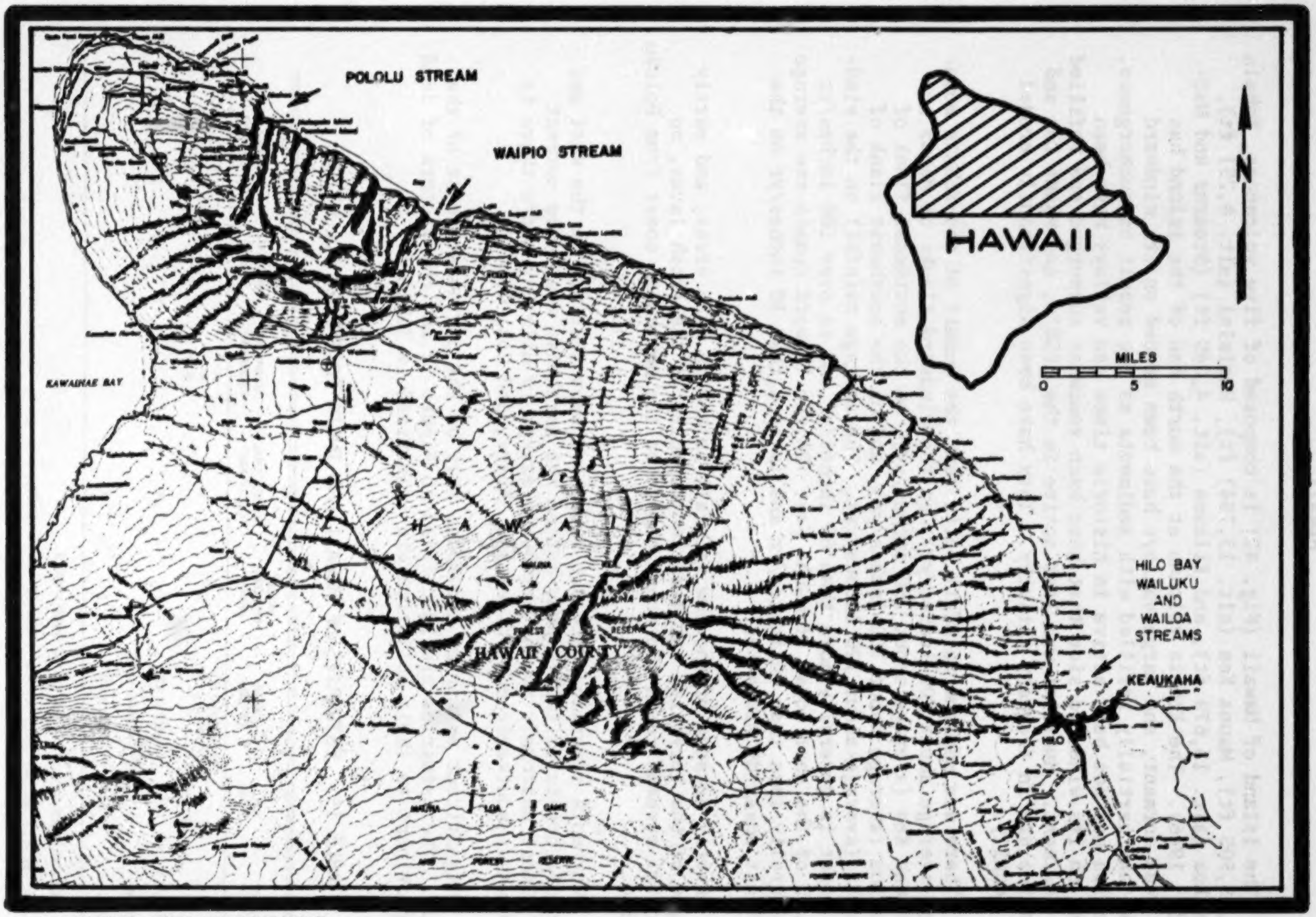
Significant estuaries are found only on the northeast coast of the island. The estuaries are identified in Figure 42 and the factors of land use pertinent to their pollution are summarized in Table 15.

TABLE 15. ESTUARIES OF HAWAII AND THEIR POTENTIAL POLLUTION.

ESTUARY SYSTEM	BAY ESTUARY	STREAM ESTUARY	WATER DEVELOPMENT	AGRICULTURAL DEVELOPMENT	INDUSTRIAL DEVELOPMENT	URBAN DEVELOPMENT	ESTUARY DEVELOPMENT
HILO		WAILOA R			M	C, S	S, R
		WAILUKU R	E[1]	S	M	S, C	
	HILO HBR				S, M	S, C	H, R, (O_S)[2], F_B
WAIPIO		WAIPIO STR	I	S, T			
WAIMANU		WAIMANU STR	I				
POLOLU		POLOLU STR	I	S			

1) REFER TO PAGES 18 - 20 FOR THE KEY TO THESE SYMBOLS.

2) THE NEW HILO SANITARY SEWER OUTFALL IS OUTSIDE THE BREAKWATER.



BASE:USGS/AMS 1/250,000 QUADRANGLE

FIGURE 42. ESTUARIES OF THE ISLAND OF HAWAII.

Hilo Harbor and Wailuku and Wailoa Rivers

Neither Hilo Bay nor Hilo Harbor is a typical estuary. Hilo Bay is simply the coastal reentrant resulting from the joining of the slopes of the volcanoes of Mauna Kea, Mauna Loa, and Kilauea. The head of this Bay was naturally protected by the Blonde Reef (coral) on which a breakwater was erected between 1908 and 1930. The harbor has been the principal port of the island since the 19th century.

"The currents within Hilo Harbor consist of a reversing component setting into and out of the harbor, superimposed upon a net drift out of the harbor resulting from the discharge of the Wailuku and Wailoa Rivers (Belt, Collins and Assoc., 1961). Velocities...appear to be less than 0.1 knot below the surface, [based] on the trajectories of dye patches... A dye patch outside of the entrance drifted to the northwest, at less than 0.1 knot, showing no digression toward the entrance on a rising tide. According to the Coast Pilot a north-northwest setting current of as much as 1 knot has been reported in the approach to the harbor, probably when the rivers are in flood." (Laevastu, Avery and Cox, 1964).

Fresh water enters Hilo Harbor by way of the Wailuku River, which has a typical but very short estuarine lower reach, and the Wailoa River, which is an estuarine spring-fed channel. Additional fresh water is discharged to the sea east of the harbor by extensive springs at Keaukaha (Figs. 42, 43).

The Wailuku River follows generally the boundary between Mauna Loa and Mauna Kea volcanoes. Although the River heads in a high-rainfall area, it obtains no flow from the Mauna Loa slope because of the high infiltration capacity of the fresh lavas on that slope. All of the flow comes from the older soil-covered Mauna Kea surface and shallow perched springs beneath it. It drains forested lands in its headwaters, sugarcane lands downstream, and suburban and urban districts of Hilo near the coast. A long-term flow record at 1070 feet altitude and some scattered records at 400 feet altitude (Terr. Planning Board, 1939; U. S. Geological Survey, 1961) suggest that the mean discharge through the esturary is about 300 mgd, the median something over 100 mgd, but the minimum is less than 10 mgd.

The average flow of the Wailoa River, which is fed by the basal Waiakea Springs from Mauna Loa lavas is on the order of 100 mgd. (Hirashima, 1965). A bagasse wall-board plant is located in the spring zone, but it has not been operated for several years. The Wailoa channel has been developed as a small-boat harbor.

Hilo Harbor is the major port of the island of Hawaii. Sugar and molasses are the principal export products, the imports include general merchandise, construction materials, and chemicals (gasoline, fertilizer, agricultural chemicals).

The city of Hilo is served partly by cesspools and partly by a sanitary sewer system which discharged raw sewage until recently into the middle of the harbor. In about mid-1966 a plant for primary treatment was opened east of the breakwater with effluent discharge about half a mile from shore in the open ocean. The cane-cleaning plant of Hilo Sugar Company, which is located on the west side of the harbor, is the source of a great deal of muddy waste

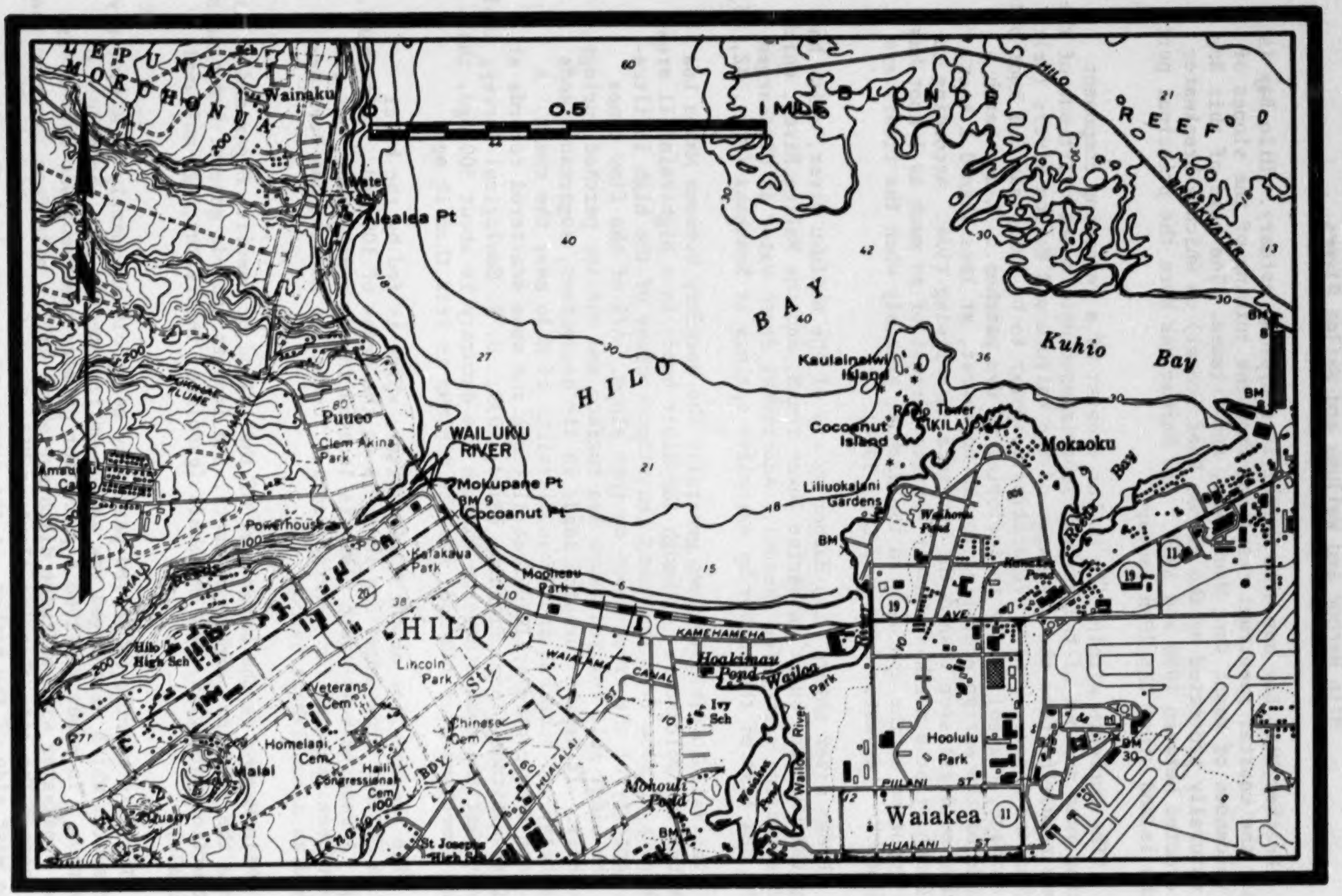


FIGURE 43. HILO HARBOR AND WAILUKU AND WAILOA RIVERS.

water and some cane trash and bagasse discharge, although efforts are made to haul the solid waste inland for disposal. The character of the wastes is similar to that of the wastes from the Honokaa Mill, located to the northwest, which have been described in detail by the Federal Water Pollution Control Administration (in preparation). At times the currents sweep the sugar mill waste water northward out of the Harbor and at other times southward into the Harbor.

Department of Health analyses of waters along the shore of the Bay for various period lengths of time within the general period from 1957 to early 1968 (Table 16) show coliform concentrations ranging in median values from 62 to 2,400 MPN/100 ml. Analyses from the Waiakea Pond have a median of 700 MPN/100 ml and an upper decile of 2,400 MPN/100 ml.

TABLE 16. COLIFORM ANALYSES FOR HILO HARBOR AND VICINITY.
(ANALYSES BY THE DEPARTMENT OF HEALTH)

				MPN/100 ML			
STATION NO.	PLACE	YEARS	N	MIN	MEDIAN	UPPER DECILE	MAXIMUM
CU1	COCONUT ISLAND BY DIVING TOWER	1957-60	37	0	700	2400	7000
CU4	COCONUT ISLAND COVE NEAR OF BATH HOUSE	1957-60	37	0	2400	2400	24000
10	COCONUT ISLAND OFF BOAT LANDING	1957-65	95	0	240	2400	24000
12A	AMERICAN LEGION	1957-68	86	0	240	2400	24000
13	EXIT OF POND: BANYAN AND KALANIANAOLE	1957-68	101	0	2400	2400	24000
	KEOKEA POINT	1964-68	184	0	6	700	2400
	COCONUT ISLAND	1966-68	35	0	240	2400	2400
	NALEI HOTEL	1966-68	34	0	240	2400	2400
	NANILOA HOTEL	1967-68	16	0	62	2400	2400
	FRONT OF COW PALACE	1967-68	16	0	700	2400	2400
	STEAK AND LOBSTER, EXIT OF POND	1966-68	32	240	2400	2400	2400
	WAIAKEA POND	1966-68	35	21	700	2400	2400

In a study before the sewage treatment plant and the new outfall were constructed, Belt, Collins and Associates (1961) found that chlorinity in the Bay varied between 10.7 percent while in the Wailoa estuary the lowest value was 2.13 percent. In the Harbor, the dissolved-oxygen levels approached 3.0 ppm, but in the Wailoa estuary, the levels of dissolved oxygen were a little higher (3.12 to 5.18 ppm). The biochemical oxygen demand was not ascertained. Coliform concentrations in the Bay were found to range from 62 to 240,000 MPN/100 ml; streptococci varied between 62 and 24,000 MPN/100 ml; and *E. coli* between 0 and 7,000 MPN/100 ml. Comparable analyses for the period since the new sewer outfall was put into operation do not appear to be available, but presumably the quality of the water has been much improved.

A fish kill in the Waiakea spring pond occurred in November 1960 involving an estimated 100 fish. The cause of the kill was undetermined (FWPCA, 1962).

Hilo Harbor is designated as a Class B coastal water. However, the water quality regulations (Department of Health, 1968) specify that: "The Class B designation shall apply only to a limited area next to boat docking facilities in bays and harbors. The rest of the water area in such bay or harbor shall be Class A water area...." This specification suggests that all of the harbor except the eastern part of Kuhio Bay should be considered Class A. The Wailuku and Wailua estuaries are presumed to be Class A waters. Whether the quality of the water in the harbor would meet even Class B standards, now that the sewage effluent is treated and discharged outside the harbor, cannot be proved with existing analyses. The quality of the water in the Wailoa River apparently will meet Class A standards with regard to coliform content but the 1960 fish kill indicates that it was not satisfactory at that time. There appears to be no analyses of the waters of the Wailuku River to indicate whether or not its quality meets the standards.

Waipio Stream

Waipio Valley, originating in the high-rainfall area in the south eastern part of the Kohala Range and cutting into the dike complex of the Range, reaches the coast along the junction of the Kohala and Mauna Kea volcano slopes. The lower part of the valley is submerged, but it has been re-filled with sediments to the general line of the coast so there is no bay estuary. The lower part of Waipio Stream is, however, tidal much of the times, although a beach bar may at times cut it off from the sea (Fig. 44).

The natural stream flow averaged many tens of millions of gallons per day. However, the normal flows are diverted for irrigation and domestic use in the upper part of the valley, and the dry weather flow reaching the coast amount probably to only a few mgd.

The valley head and north wall are in forest reserve, the east side of the valley is in sugar cane cultivation, and part of the floor of the valley is still cultivated for taro. The Peace Corps has a field training camp in the valley and uses the water for its domestic supply.

Waipio Stream, because of its tidal nature, must be included in the Class A coastal waters. No evidences of sanitary pollution have been reported. The discharges of the taro patches are muddy at times, but the flows are small. The stream itself is, of course, muddy during storm flow periods. There are no analyses to indicate whether or not the waters meet the Class A quality standards.

Pololu Stream

Pololu Valley is in geomorphology similar to Waipio Valley, except that it was cut entirely within Kohala lavas. A late Kohala lava flow of

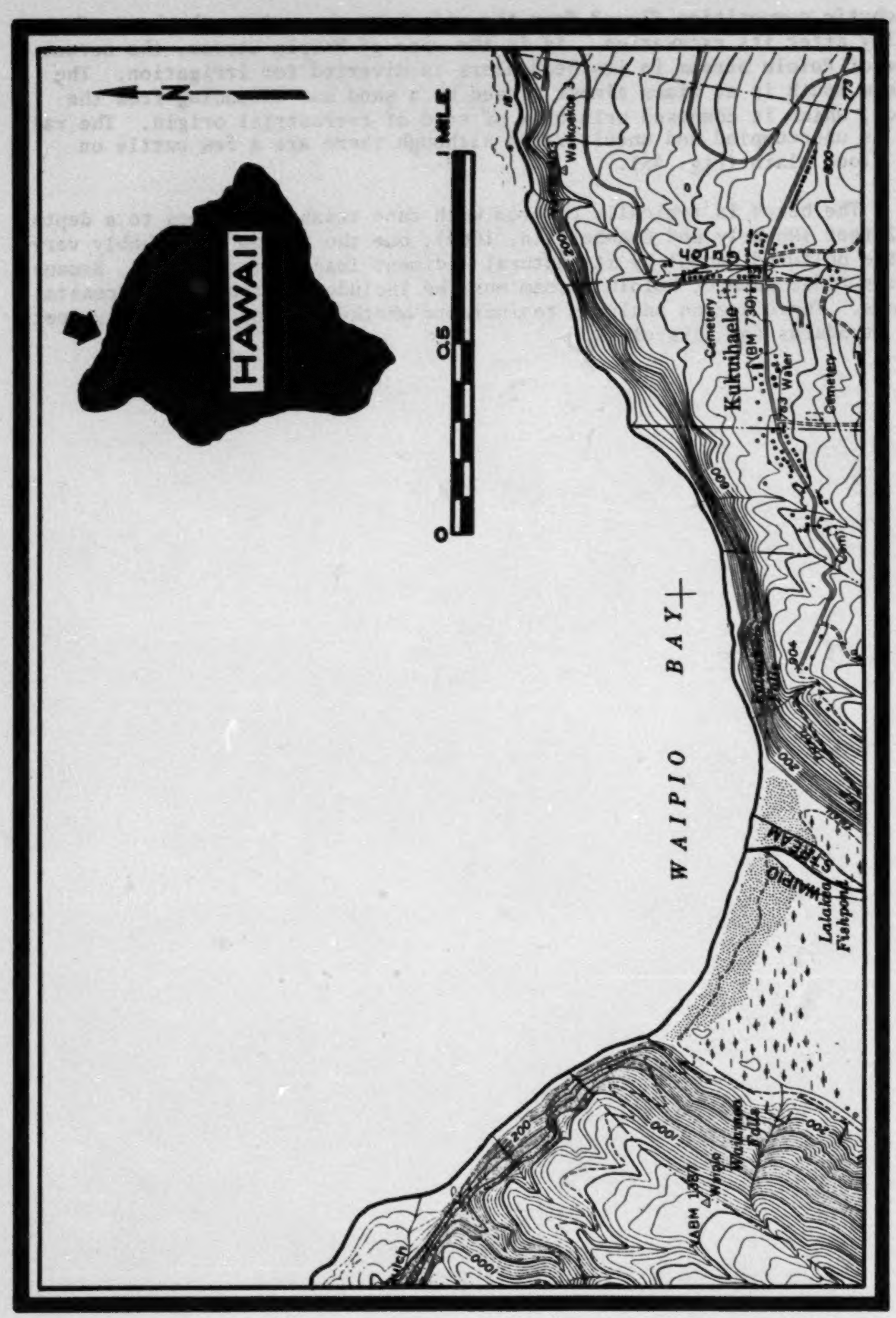


FIGURE 44. WAIPIO STREAM.

trachytic composition flowed from the rift zone above into the head of the valley after its excavation. As in the case of Waipio Stream, the normal flow of Pololu Stream in its headwaters is diverted for irrigation. The stream mouth is at times almost closed by a sand bar extending from the beach, which is composed primarily of sand of terrestrial origin. The valley is unoccupied and uncultivated although there are a few cattle on the flood plain (Fig. 45).

The beach is typically covered with cane trash, sometimes to a depth of 2 feet (Moberly and Chamberlain, 1964), but the stream is probably very little polluted except by its natural sediment load during storms. Because of its tidal nature, Pololu Stream must be included in the Class A coastal waters. There are no analyses to indicate whether or not its quality meets the standards for this class.

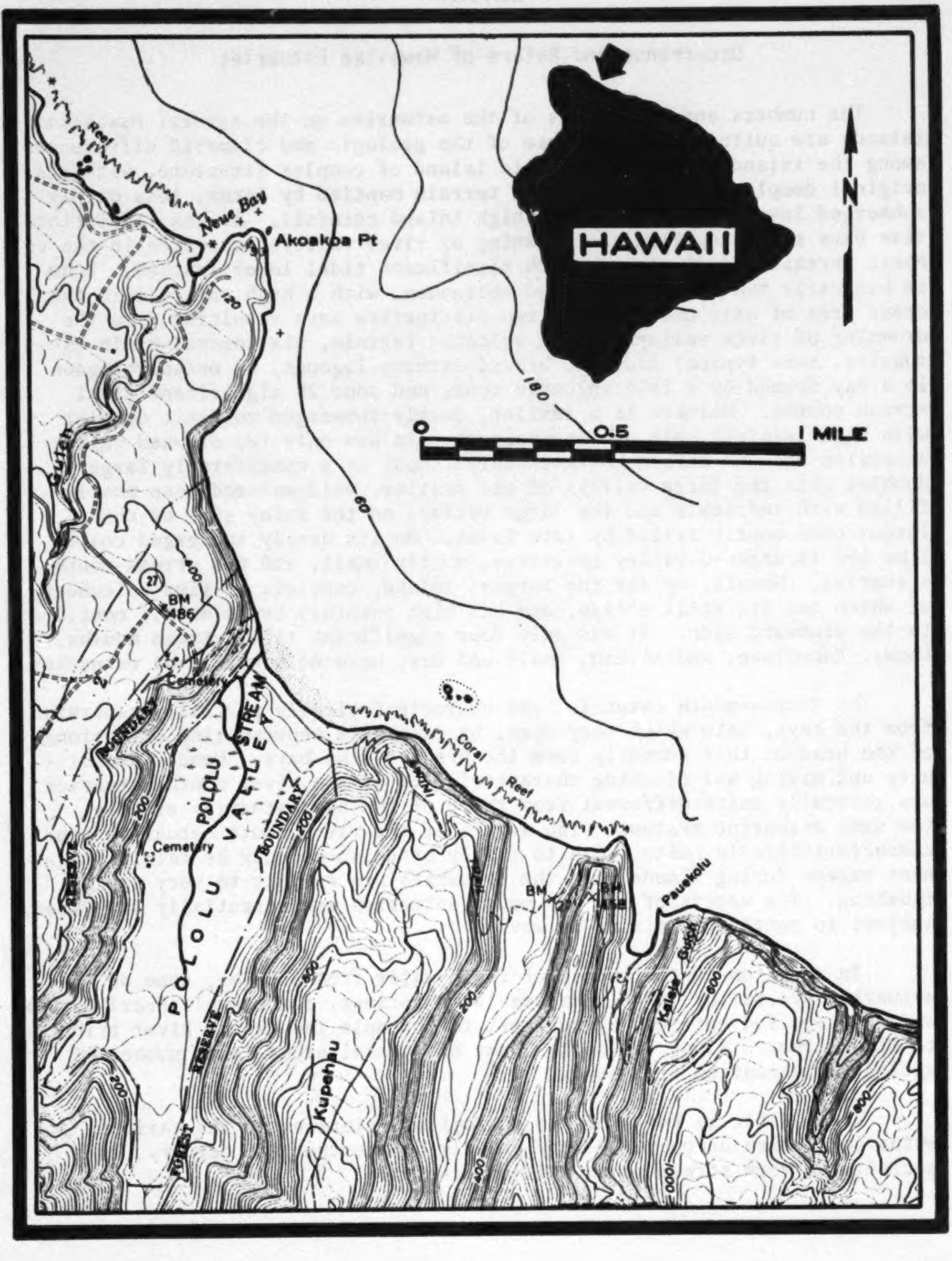


FIGURE 45. POLOLU STREAM.

SUMMARY

Occurrence and Nature of Hawaiian Estuaries

The numbers and characters of the estuaries on the several Hawaiian islands are quite diverse because of the geologic and climatic differences among the islands. Kauai is an old island of complex structure, with its original deeply submerged volcanic terrain mantled by later, less deeply submerged lavas, and with a very high inland rainfall. It has 11 distinctive bays resulting from the drowning of river valleys excavated in the volcanic terrain and 15 streams with significant tidal lower reaches. Oahu is basically two deeply submerged volcanoes, with a high rainfall in the crest area of only one. It has two distinctive bays resulting from the drowning of river valleys in the volcanic terrain, six coastal-plain estuaries, some typical and some hybrid estuary-lagoons, an estuary-lagoon in a bay formed by a late volcanic cone, and some 20 significant tidal stream mouths. Molokai is a smaller, deeply submerged volcanic doublet with high rainfall only one one segment. It has only two-drowned valley estuaries and one stream-mouth estuary. Maui is a considerably larger doublet with the large valleys of the smaller, well-watered cone mostly filled with sediments and the large valleys on the rainy side of the larger cone mostly filled by late lavas. On its deeply submerged coastline are 14 drowned-valley estuaries, mostly small, and two stream-mouth estuaries. Hawaii, by far the largest island, consists of five volcanoes, of which two are still active, and has high rainfall areas mostly confined to the windward side. It has only four significant tidal stream mouths. Lanai, Kahoolawe, and Niihau, small and dry, have no sigfificant estuaries.

The stream-mouth estuaries are characteristically partially separated from the bays, into which they open, by sand bars representing extensions of the beaches that normally form the heads of the bays. Hence the salinity and mixing and flushing characteristics of the river mouth estuaries are generally quite different from those of the bay estuaries even in the same estuarine systems. The waters of the river mouth estuaries are characteristically quite fresh to fairly brackish and may be fairly stagnant except during floods when the estuaries are subject to very rapid flushing. The waters of the bay mouth estuaries are essentially sea water, subject to continuous mixing by waves.

In addition to the supply of fresh water from streams, some of the estuaries are fed by large near-sea-level springs, for example Pearl Harbor, and some are fed entirely by springs, for example the Wailoa River tributary to Hilo Harbor. Along the south coast of Molokai are a large number of spring-fed estuarine fish ponds.

Very little is known of the ecological relations in the various estuaries, which undoubtedly vary greatly from estuary to estuary, especially between stream-mouth and bay estuaries.

Economic Development, Estuarine use, Estuarine Changes, and Sources of Estuarine Pollution

The estuaries and some estuary-like bays have contributed greatly to the economic development of the islands. Honolulu Harbor, on Oahu, the principal commercial harbor of the state of Hawaii, which was originally a minor estuary and associated reef inlet, has now been much modified by dredging and filling. Pearl Harbor, the famous naval port on Oahu, is a coastal-plain estuary, typical except for the extent of its development. Nawiliwili Harbor, the major port of Kauai, occupies a part of Nawiliwili Bay, the best developed estuary in the islands resulting from the drowning of a valley cut in lavas. Port Allen, also on Kauai, occupies a part of Hanapepe Bay, another drowned-valley estuary. Kahului and Hilo Harbors, the principal ports of the islands of Maui and Hawaii, respectively, are not natural estuaries but have some estuarine features. The use of these estuaries as harbors subjects them, of course, to the usual problems of port contamination.

Many of the estuaries of the state, even some of those serving as military and commercial harbors, are used for fishing. Commercial fishing is generally restricted to the catch of the bait fish, nehu, in the larger bays such as Pearl Harbor, Kaneohe Bay, Kaiaka Bay, and Honolulu Harbor on Oahu, and Hanalei Bay on Kauai. Recreational fishing, however, is practiced in practically all of the estuaries.

Many of the estuaries are intensively used as swimming areas, and some have fringing reefs used for surfing. To promote such use, county parks have been established on the beaches of Hanapepe, Hanamaulu, Anahola, and Hanalei Bays of Kauai and Kahana Bay, Waimea, and Haleiwa Bays on Oahu.

Many of the estuaries, in addition, are famous scenic spots, for example Hanalei Bay on Kauai.

A few of the estuaries and the streams tributary to them are still in wilderness areas and hence essentially in natural condition. Even these estuaries carry very heavy sediment loads during flood periods.

From most of the streams tributary to the estuaries, the normal flows have been diverted inland for irrigation. The resulting reduction in dry-weather flows has led to increased sand-bar development and increased separation between stream mouths and bays and has increased stagnation in the stream mouths.

Most of the streams, particularly on the islands other than Oahu, drain lands in intensive agricultural use, principally sugar cane and pineapple cultivation, and are subject to pollution from fertilizers, accelerated erosion, and possibly other pollutants. Some drain ranch lands from which bacterial contamination may be derived.

Wastes from sugar mills and pineapple canneries reach some of the estuaries. Sugar-mill wash water containing soil and some cane trash and other contaminants is discharged directly into Hilo Bay. Sugar-mill wastes reach Pearl Harbor by way of an irrigation system and other estuaries are reached by drift in the ocean. Cannery wastes with more or less treatment reach Honolulu Harbor and an estuarine canal on Kauai.

The estuarine character of a small coastal plain on Kauai has been greatly changed by channel development, but the greatest changes have occurred on Oahu, particularly in the Honolulu area where all of the original streams now reach the sea or bays by way of canals, where ship and small-boat channels have been cut through the reef, and where great areas of original swamp and reef have been drained and filled.

Urban wastes contribute to the pollution problems of estuaries on all of the islands, but most particularly on Oahu where the population density is the highest. Most of the smaller villages throughout the islands, and a considerable part of Honolulu, are served by cesspools. Where these drain properly, they may contribute to the nutrient contamination but they are unlikely to contribute to bacterial contamination of the estuaries. However, in areas of poor drainage their overflows may be quite significant sources of contamination of both kinds. Most of the sewage collected in sewer systems is treated adequately to make bacterial contamination insignificant, although again nutrient contamination may be significant. From a few sewer systems, however, notably that of Honolulu, raw sewage is discharged. The Honolulu outfall is on the open coast, but its effluent may reach the Kalihi-Keehi estuary and perhaps others under certain wind and current conditions.

Much of the urban pollution of estuaries occurs, however, by way of storm drainage. A large fraction even of the bacterial contamination may be introduced by this route, and the sediment loads delivered may be very high, particularly from lands being developed for residential use.

The obvious effects of the pollution of Hawaiian estuaries are still limited. Most are subject to discoloration and high turbidity during floods, and a few are continuously muddy. Cane trash is common in some. Oil is common in some of the commercial harbors, and oil drifting in from the outside sometimes contaminates other estuaries. Some of the drainage canals, particularly, are carriers of urban trash. Very locally there are odoriferous mudflats and other evidences of anaerobic conditions. A few fish kills have been recorded.

Water Quality and Water-Quality Standards

As a basis for controlling the quality of coastal waters of the State in general, including the waters of the estuaries, these waters have been divided into three classes: *Class AA* special coastal waters in which essentially the natural quality is intended to be maintained, *Class A*, the greater part of the coastal waters in which a quality high enough for swimming, fishing, and other recreational uses is intended to be maintained; and *Class B*, restricted waters in which only minimum quality standards are intended to be maintained consistent with harbor usage. For each class, certain numerical standards of water quality have been established.

For most of the estuaries of the State, the water-quality information available is insufficient for conclusive determination whether or not the standards are met under present conditions. It is obvious that a great deal more data is required to prove that the water quality in a given estuary meets the standards for the pertinent class than to prove that it does not. Where the analyses are insufficient to prove that the quality of water in an estuary will not meet the pertinent standard, a comparison with estuaries having similar sources of pollutants and similar characteristics may provide an index of its probable water-quality conditions. Although the subjectivity involved may make quite questionable the appraisals of water quality relative to pertinent standards in individual estuaries, useful conclusions may be drawn from a summary of such appraisals. Such a summary is presented in Table 17.

TABLE 17. SUMMARY OF WATER QUALITY IN HAWAIIAN ESTUARIES IN RELATION TO STANDARDS FOR COASTAL WATERS.

			WATER QUALITY			
ESTUARY TYPE	COASTAL WATER CLASS	TOTAL	(A) PROBABLY MEETS STANDARDS	(B) PROBABLY DOES NOT MEET STANDARDS	(C) DOES NOT MEET STANDARDS	(D) INSUFFICIENT DATA FOR JUDGEMENT
STREAM-MOUTH ESTUARIES DISCUSSED IN REPORT	A	30	1	6	5	18
ESTUARINE CANALS DISCUSSED IN REPORT	A	4	0	1	3	0
ADDITIONAL MINOR STREAM-MOUTH AND CANAL ESTUARIES TRIBUTARY TO BAY ESTUARIES (PEARL HARBOR, KEEHI LAGOON, HONOLULU HARBOR, AND KANEOHE BAY)	A	14	0	11	3	0
TOTAL STREAM MOUTH AND CANAL ESTUARIES	A	48	1	18	11	18
BAY ESTUARIES AND ESTUARINE HARBORS	AA	14	11	0	3	0
(A BAY OR HARBOR WITH TWO CLASSES OF WATERS IS LISTED AS TWO ESTUARIES)	A	17	4	5	5	3
	B	10	1	3	2	4
TOTAL		41	16	8	10	7

In general, the only water quality parameter that has been monitored over a sufficient length of time to provide anything approaching a satisfactory base for determining present normal quality in the estuaries is the total coliform concentration. For most estuaries there are no stations at which even this parameter has been monitored. Analyses of fecal coliform concentrations, pH, nutrients, oxygen, dissolved solids, temperature, turbidity, and suspended materials are rare and analyses of herbicides and pesticides almost non-existent. Reporting of trash and oil has been sporadic.

CONCLUSIONS

The estuaries of the Hawaiian Islands are of interest, in spite of their generally small size, because of the diversity of their occurrence and ecology. They are of great value because of their utility as harbors, fisheries, recreational areas, and channels for sewage disposal and for their attractiveness. Some of these uses, of course, conflict with others.

Some of the estuaries are still in essentially natural condition, others have been much altered, and many are demonstrably polluted. Sediment discharge occurs through even estuaries in natural conditions.

For nearly half of the stream-mouth estuaries, the analyses of water quality available are insufficient to provide any basis for judging whether or not the pertinent established standards (Class A except in a small-boat harbor in one) are met. In two thirds of the fraction for which available analyses provide some basis for judgement, the water quality does not meet the established standards, and in most of the rest it probably does not meet the standards. Probably the water quality of none of the estuarine canals meets the pertinent established standards (Class A).

The water quality of the bay estuaries or portions of bay estuaries designated for maintenance of high quality (Class AA) probably meets the pertinent established standards in the case of most of the estuaries on Molokai and Maui, but not in the designated portions of the West Loch of Pearl Harbor, Kaneohe, Kahana, and Waialua Bays on Oahu or Hanalei Bay on Kauai. For nearly half the harbors, the available analyses are insufficient to provide any basis for judgement. In the rest, the water quality does not meet or probably does not meet the pertinent established standards (Class B). In more than half of the other bay estuaries the water quality probably does not meet the pertinent established standards (Class A), and in most of the remainder no judgement can be made.

From these direct conclusions other indirect conclusions and questions may be drawn.

The fact that the available analyses, even for the single most commonly measured parameter (total coliforms), provide an insufficient base for sound judgement as to whether the established standards are met in most of the estuaries,indicates that a water quality monitoring program of much greater geographic coverage must be initiated. The fact that other significant parameters have been analyzed only for a token number of estuaries indicates that the monitoring program needs to be extended to cover many more parameters of importance. A program expanded both in geographic extent and number of parameters included has been planned by the Department of Health, but funds have not yet been provided for its implementation.

The evidence that the water quality in none of the estuarine drainage canals meets the standards for the Class A waters in which they are now included, raises the question whether these estuaries as a group should perhaps more appropriately be included with the harbors in Class B. The answer to the question depends upon more knowledge concerning the sources of their pollution, possible methods of reduction of the pollution, the costs of such reduction, and the benefits to be derived from meeting the higher standards than is now found.

The same sort of evidence concerning the Class AA estuaries or portions of estuaries raises the question whether they should perhaps more appropriately be included in Class A, or at least reduced in extent. The answer to this question depends on the same sort of additional knowledge required in the previous one.

The evidence that the water quality in so many estuaries of all classes and types violates the present standards indicates that the standards had to be adopted on the basis of far too little knowledge of the natural backgrounds or of the ecological, economic, and esthetic effects of changes in the concentrations of the various pollutants recognized in the standards. For example, with respect to the three pollution parameters which perhaps most commonly lead to violations of the present standards, the following information seems essential:

1. Total coliform concentrations
    a. Relative importance of sewer system effluents, cesspool seepage, cesspool overflow, and general surface discharge in contributing to estuarine concentrations.
    b. Significance in sea waters as indicators of health hazards.
2. Fecal coliform concentrations
    a. Relative importance of sewer system effluents, cesspool seepage, cesspool overflow, and general surface discharge in contributing to estuarine concentrations.
3. Sediments
    a. Natural discharge rates and historic trends in discharge rates.
    b. Relative contributions of agricultural, industrial, and general urban areas to discharges.
    c. Adequacy of present urban regulations and enforcement of present regulations on urban land-development practices relative to erosion control.
    d. Ecological effects.

The uncertainty of general ecological effects and health hazards of some pollutants and potential pollutants indicates that research on these effects as they pertain to estuaries must be considered as just beginning or not yet begun. Examples are the herbicides and insecticides, for which a very small amount of background information is available, and the viruses for which essentially no information is available.

In short, although the present classification of coastal waters and standards adopted for the various classes provide a basis for regulatory action that can result in the improvement of water quality of Hawaiian estuaries, extensive monitoring is required to render the regulatory system even minimally effective, and a great deal of ecological, technological, and socio-economic research will be required to provide a basis for adjustments in the classification and standards that will be found necessary to the maximum effectiveness of the system.

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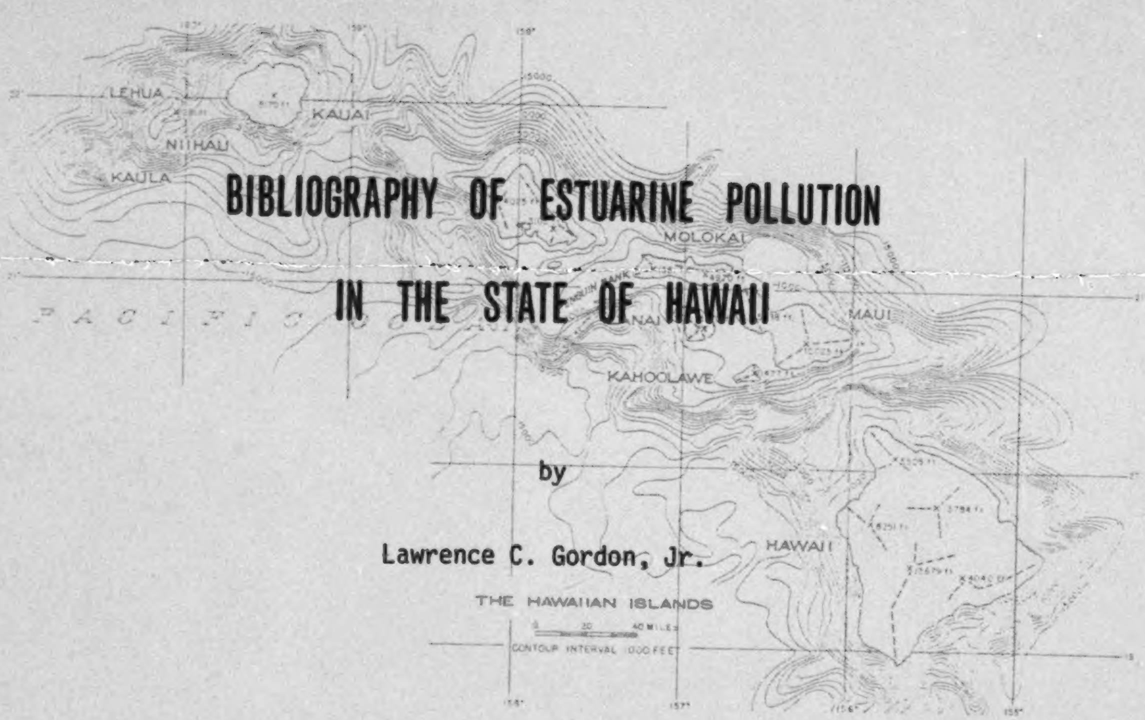
by

Lawrence C. Gordon, Jr.



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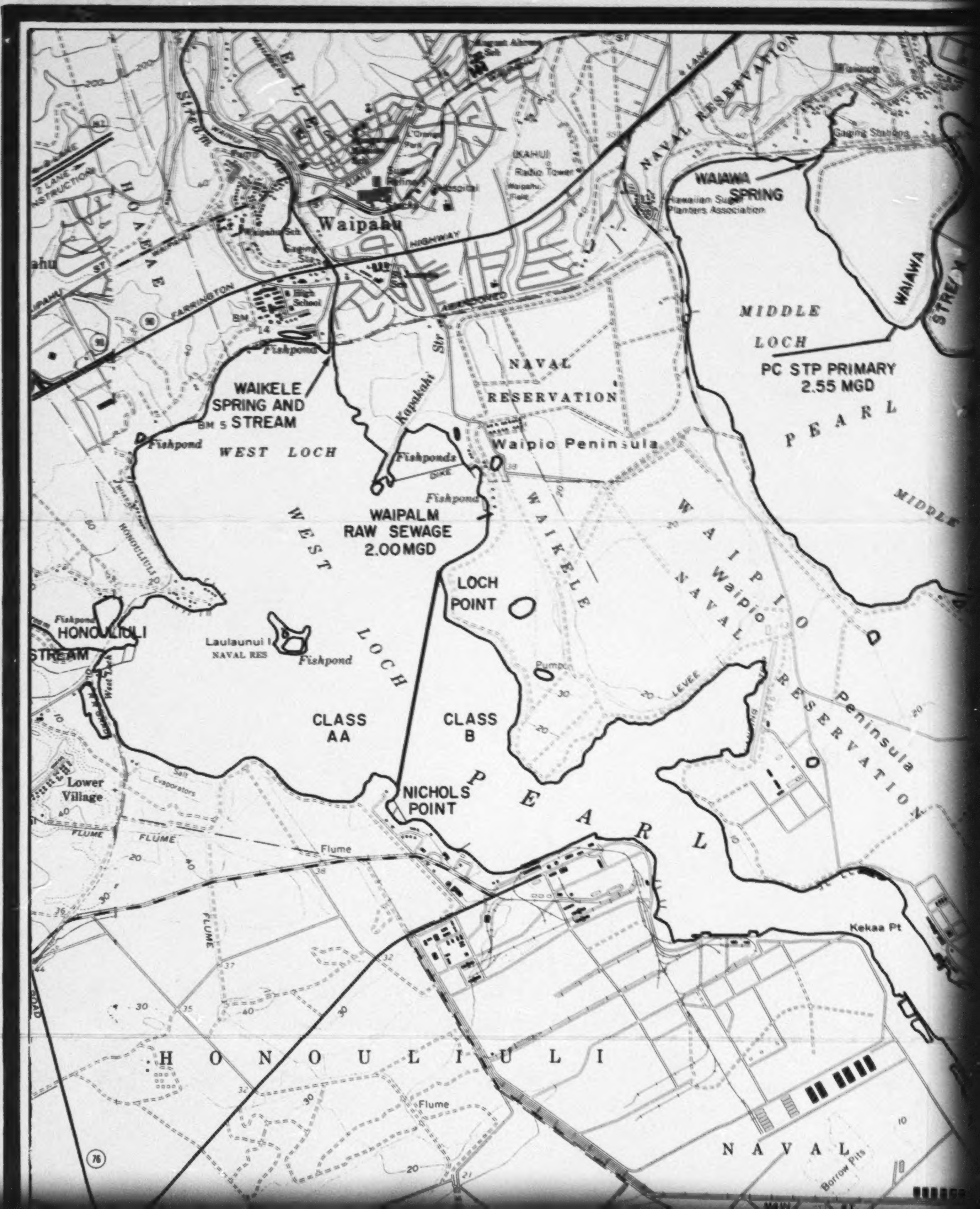
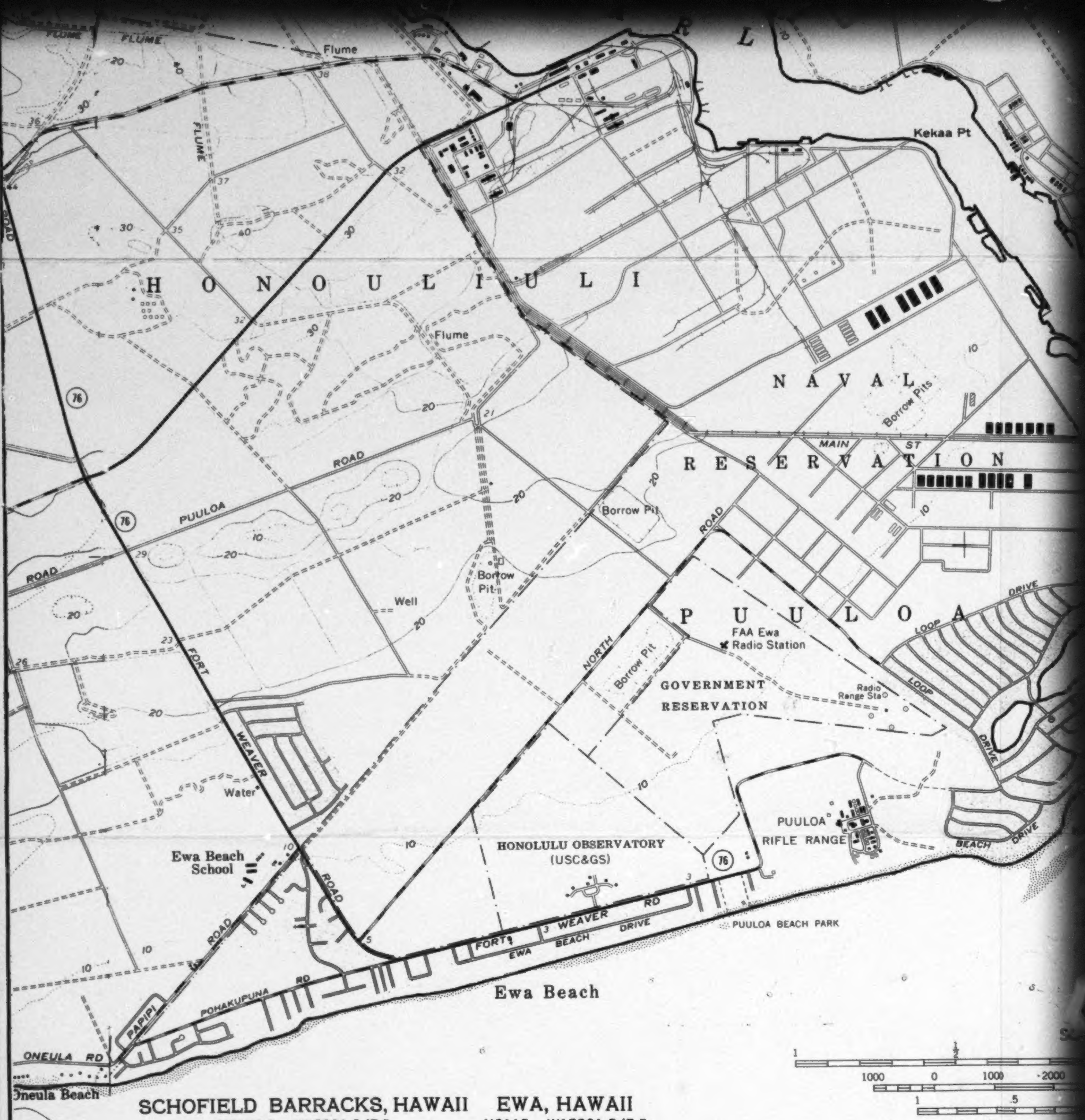

Waipahu
WAIAWA SPRING
Hawaiian Sugar Planters Association
Gaging Stations
NAVAL RESERVATION
(KAHU) Radio Tower
Hospital
Sugar Refinery
HIGHWAY
FARRINGTON
High School
2 LANE CONSTRUCTION
Fishpond
WAIKELE SPRING AND STREAM
BM 5
WEST LOCH
Fishponds
DIKE
Kapakahi Str
NAVAL RESERVATION
Waipio Peninsula
MIDDLE LOCH
PC STP PRIMARY 2.55 MGD
PEARL
WAIAWA STREAM
MIDDLE
WAIPALM RAW SEWAGE 2.00 MGD
WEST LOCH
LOCH POINT
WAIKELE
WAIPIO
Waipio Peninsula
NAVAL RESERVATION
HONOULIULI STREAM
Laulaunui I
NAVAL RES
CLASS AA
CLASS B
Pump
LEVEE
Lower Village
Salt Evaporators
NICHOLS POINT
PEARL
FLUME
Flume
Kekaa Pt
HONOULIULI
NAVAL
Borrow Pits
76



SCHOFIELD BARRACKS, HAWAII
N2122.5—W15801.5/7.5
1967

EWA, HAWAII
N2115—W15801.5/7.5
1962

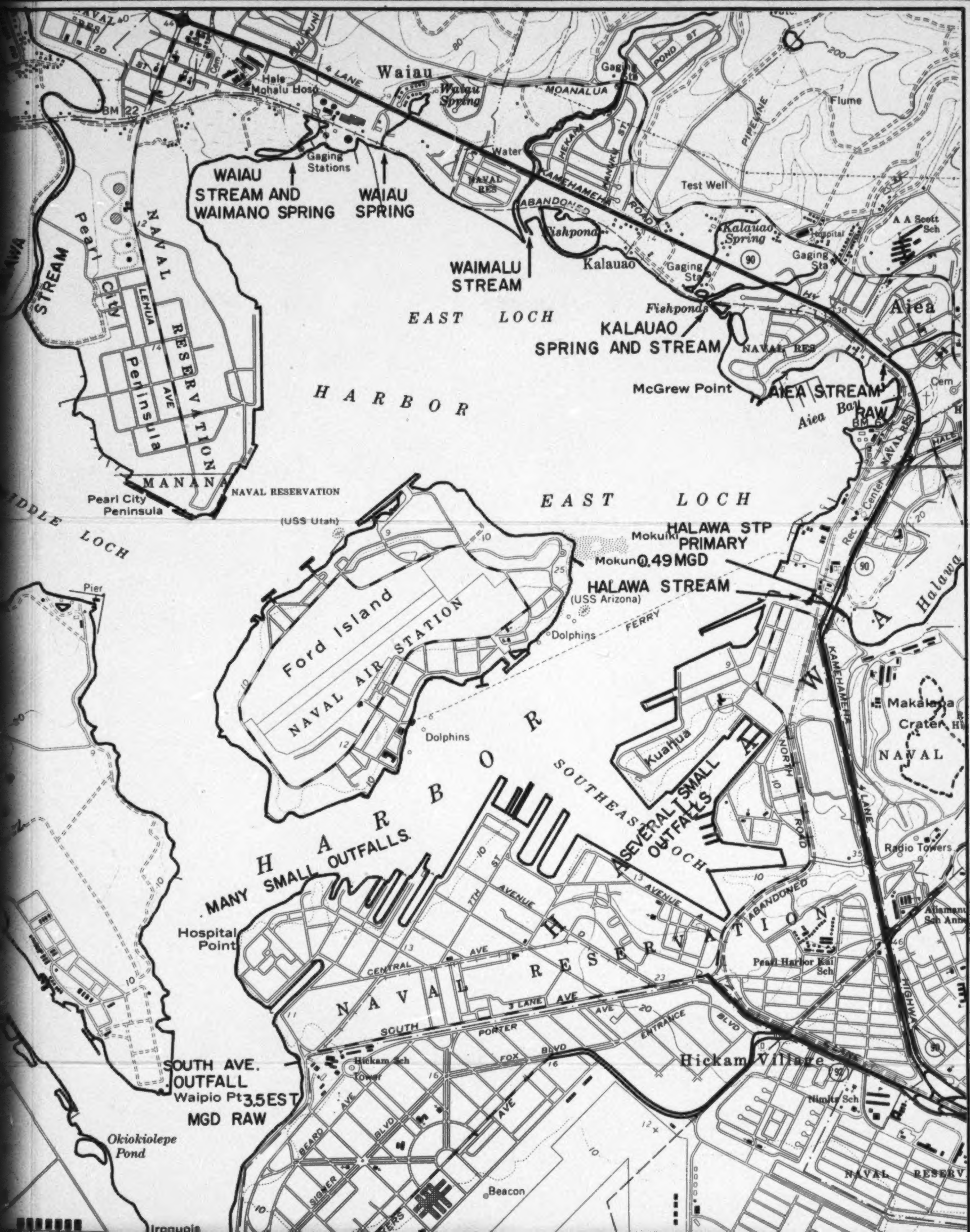
WAIPAHU, HAWAII
N2122.5—W15754/7.5
1959

PUULOA, HAWAII
N2115—W15754/7.5
1959

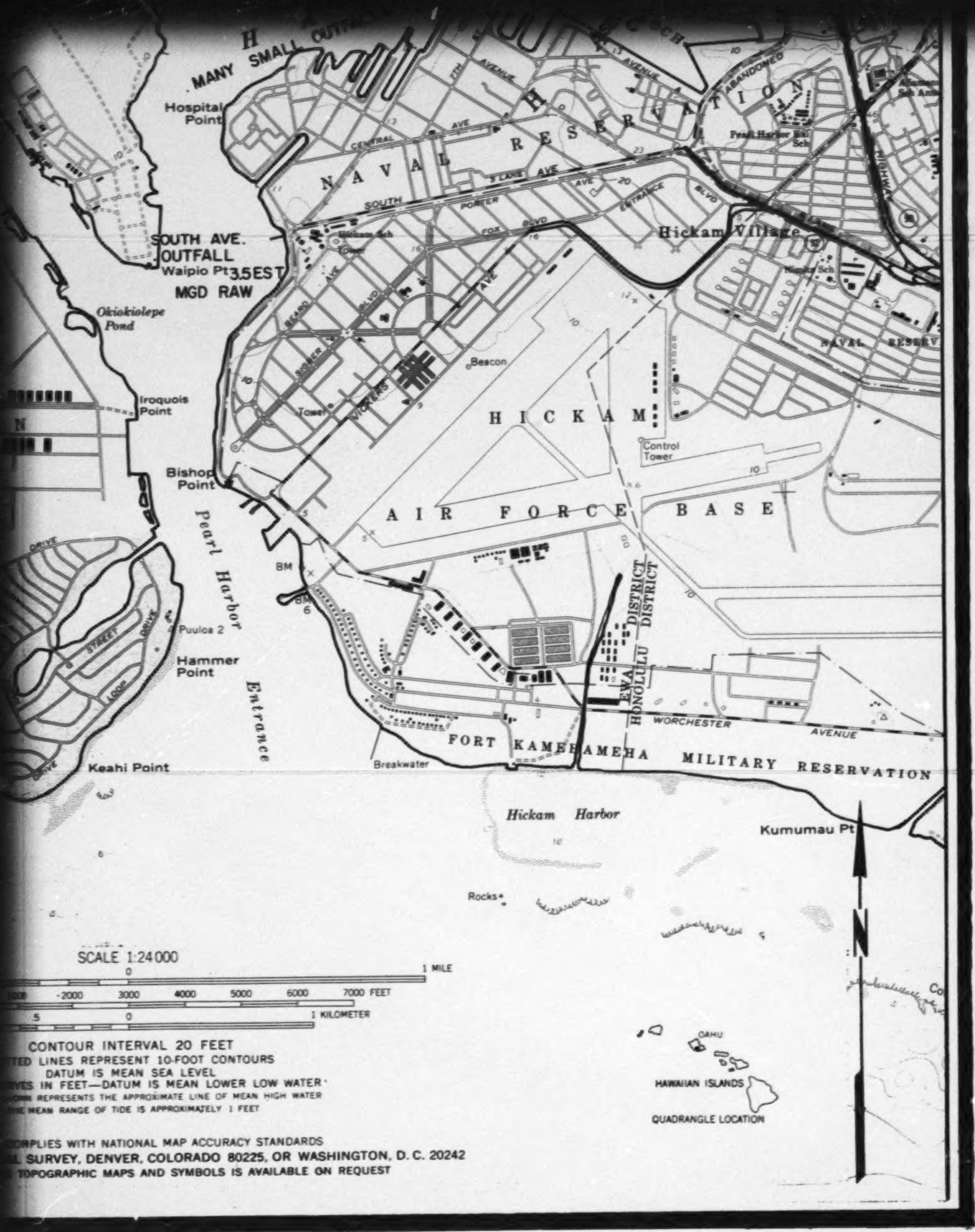
CONTOU
DOTTED LINES RE
DATUM
DEPTH CURVES IN FEET
SHORELINE SHOWN REPRESENT
THE MEAN RANGE

THIS MAP COMPLIES WIT
FOR SALE BY U.S. GEOLOGICAL SURVEY,
A FOLDER DESCRIBING TOPOGRAPH

PLATE I PEARL



WAIAU STREAM AND WAIMANO SPRING
WAIAU SPRING
WAIMALU STREAM
KALAUAO SPRING AND STREAM
AIEA STREAM RAW
HALAWA STP PRIMARY 0.49 MGD
HALAWA STREAM
MANY SMALL OUTFALLS.
SEVERAL SMALL OUTFALLS
SOUTH AVE. OUTFALL 3.5 EST MGD RAW
Waiau
Waiau Spring
Hale Mohalu Hosp
Gaging Stations
Water
MOANALUA
POND ST
PIPELINE
Flume
Test Well
NAVAL RES
KAMEHAMEHA ROAD
ABANDONED
Fishpond
Kalauao
Kalauao Spring
Gaging Sta
Hospital
A A Scott Sch
Aiea
Fishponds
NAVAL RES
McGrew Point
Aiea Bay
Cem
EAST LOCH
HARBOR
Pearl City Peninsula
LEHUA
AVE
NAVAL RESERVATION
STREAM
MANANA
NAVAL RESERVATION
Pearl City Peninsula
MIDDLE LOCH
(USS Utah)
Mokuiki
Mokunui
(USS Arizona)
Dolphins
FERRY
Ford Island
NAVAL AIR STATION
Dolphins
Pier
Rec Center
Halawa
Makalapa Crater
NAVAL
KAMEHAMEHA
4 LANE
Kuahua
NORTH ROAD
Radio Towers
SOUTHEAST LOCH
PEARL HARBOR
Hospital Point
7TH ST
AVENUE
13 AVENUE
ABANDONED
Pearl Harbor Kai Sch
Aliamanu Sch Annex
CENTRAL AVE
NAVAL RESERVATION
3 LANE AVE
SOUTH AVE
PORTER AVE
ENTRANCE BLVD
FOX BLVD
HIGHWAY
Hickam Village
Hickam Sch
Tower
Nimitz Sch
Waipio Pt
Okiokiolepe Pond
BEARD AVE
BLVD
AVE
SIGNER
Beacon
NAVAL RESERV
Iroquois



SCALE 1:24 000

0 1 MILE

1000 2000 3000 4000 5000 6000 7000 FEET

.5 0 1 KILOMETER

CONTOUR INTERVAL 20 FEET

TED LINES REPRESENT 10-FOOT CONTOURS

DATUM IS MEAN SEA LEVEL

RVES IN FEET—DATUM IS MEAN LOWER LOW WATER

SHOWN REPRESENTS THE APPROXIMATE LINE OF MEAN HIGH WATER

THE MEAN RANGE OF TIDE IS APPROXIMATELY 1 FEET

COMPLIES WITH NATIONAL MAP ACCURACY STANDARDS

AL SURVEY, DENVER, COLORADO 80225, OR WASHINGTON, D. C. 20242

TOPOGRAPHIC MAPS AND SYMBOLS IS AVAILABLE ON REQUEST

PEARL HARBOR